Cover picture, showing a ventilation fan,
was kindly provided by Messrs. P. Zettwoog and
Y. François, Département de Protection,
Centre d'Études Nucléaires, Fontenay-aux-Roses, France.
RADON IN URANIUM MINING
The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN  HAITI  PARAGUAY
ALBANIA  HOLY SEE  PERU
ALGERIA  HUNGARY  PHILIPPINES
ARGENTINA  ICELAND  POLAND
AUSTRALIA  INDIA  PORTUGAL
AUSTRIA  INDONESIA  ROMANIA
BANGLADESH  IRAN  SAUDI ARABIA
BELGIUM  IRAQ  SENEGAL
BOLIVIA  IRELAND  SIERRA LEONE
BRAZIL  ISRAEL  SINGAPORE
BULGARIA  ITALY  SOUTH AFRICA
BURMA  IVORY COAST  SPAIN
BYELORUSSIAN SOVIET SOCIALIST REPUBLIC  JAMAICA  SRI LANKA
CANADA  JAPAN  SUDAN
CHILE  JORDAN  SWEDEN
COLOMBIA  KENYA  SWITZERLAND
COSTA RICA  KHMER REPUBLIC  SYRIAN ARAB REPUBLIC
CUBA  KOREA, REPUBLIC OF  THAILAND
CYPRUS  KUWAIT  TUNISIA
CZECHOSLOVAKIA  LIBERIA  TURKEY
DEMOCRATIC PEOPLE'S REPUBLIC OF KOREA  LIBYAN ARAB REPUBLIC  UGANDA
DENMARK  LEBANON  UKRAINIAN SOVIET SOCIALIST REPUBLIC
DOMINICAN REPUBLIC  LIECHTENSTEIN  UNION OF SOVIET SOCIALIST REPUBLICS
ECUADOR  LUXEMBOURG  UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
EGYPT  MADAGASCAR  UNITED REPUBLIC OF CAMEROON
EL SALVADOR  MALAYSIA  UNITED STATES OF AMERICA
ETHIOPIA  MALI  URUGUAY
FINLAND  MAURITIUS  VENEZUELA
FRANCE  MEXICO  VIET-NAM
GABON  MONGOLIA  YUGOSLAVIA
GERMAN DEMOCRATIC REPUBLIC  MOROCCO  ZAIRE
GERMANY, FEDERAL REPUBLIC OF  NETHERLANDS  ZAMBIA
GHANA  NEW ZEALAND
Greece  NIGER  PANAMA
GUATEMALA

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

Printed by the IAEA in Austria
March 1975
RADON IN URANIUM MINING

PROCEEDINGS OF A PANEL
ON RADON IN URANIUM MINING
ORGANIZED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
AND HELD IN
WASHINGTON, D.C., 4-7 SEPTEMBER 1973

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1975
A considerable increase in uranium production capacity is foreseen over the next decades to provide fuel for a rapidly expanding nuclear power industry. The problems that arise with this anticipated increase in production have far reaching implications on, for example, availability of ore, mining methods, mine and mill construction facilities, environmental impacts, all of which require careful attention within the uranium mining industry.

The International Atomic Energy Agency is concerned in assisting with the study of all such problems, including, among others, the effect which radiological and waste management legislative controls will have on uranium costs and ore reserves. The essential requirement is that the health of uranium miners should be safeguarded. Most Governments of uranium-producing countries already have legislation limiting the permissible amounts of radon in working uranium mines, and many have also indicated that permitted levels may be more rigorous in future years. To comply with these regulations uranium mining companies and organizations must invest considerable sums on new ventilation and protective systems. This expenditure will, in many cases, increase the total cost of uranium production and, in some mines, may raise the cost above acceptable economic limits. The present estimated uranium reserves are classified on the basis of 'estimated cost of production' figures and these may, therefore, require modification. This, in turn, might affect the uranium fuel situation for future nuclear power programmes.

To discuss this, and the related subjects of mine ventilation and radon emanation in mines, the Agency convened a Panel on Radon in Uranium Mining from 4 to 7 September 1973 which, at the invitation of the United States Government, was held in Washington, D.C. Nine participants and nine observers from six countries were present at the meeting.

The principal subject was the theme of the first session. It was recognized that, while the main effect of radiological and waste management legislative controls is on prices and reserves, there are many important contributory factors which require study, such as the future impact on uranium exploration activity, uranium demand, present sales contracts, future sales contracts and the sociological effects on mining communities. An examination was made of what limit of severity the industry could tolerate in regard to further tightening of radiation exposure standards without severe consequences to uranium supplies, with the resulting serious implications for future nuclear power planning.

It is probable that in future much of the new uranium supplies will have to come from new mines opened not only in the existing uranium-producing countries but also extensively in developing countries over the next decades. The Agency wishes to be able to advise future uranium producers, particularly in developing countries, of the requisite radiation exposure standards necessary to avoid harm to workers in the industry and of what the effect of these standards will be on economics, mine planning and production.

One particularly useful and practical aspect of such assistance will be to provide advice on the design and engineering of good ventilation systems in new mines. Ventilation was, therefore, the theme of the second session of the Panel; it covered technical problems of mine ventilation specifically related to the elimination of radon gas from underground and deep open-pit uranium mines.

The subject of the third session of the Panel was the phenomenon of radon emanation and the mode of radon release, which is a complex function of U\textsubscript{3}O\textsubscript{8} content, type of uranium mineralogy, host rock character, porosity, etc. This study is obviously basic and fundamental to the main subject.

The Agency is grateful to all the experts who took part in the Panel meeting, especially to those who contributed papers, took part in the discussions or helped to prepare the Summary Reports on the three main subjects. Particular thanks are due to the chairman, Mr. Frank E. McGinley, Chief of the Engineering and Safety Branch of the USAEC at Grand Junction, Colo., who guided the work of the entire Panel and contributed substantially to the preparation of the reports.
CONTENTS

EFFECTS OF RADIOLOGICAL AND WASTE-MANAGEMENT LEGISLATIVE CONTROLS ON URANIUM COSTS AND ORE RESERVES (Session 1)

Effects of stricter radiation exposure standards on uranium costs and ore reserves
   (IAEA-PL-565/6) .................................................. 3
   F.E. McGinley
   Discussion .......................................................... 10
Incidence des normes de radioprotection sur le marché de l’uranium (IAEA-PL-565/2) ........................................... 15
   Y. François, J. Pradel, P. Zettwoog
   Discussion .......................................................... 34
Effects of radiological and waste-management legislative controls on uranium production costs with specific reference to the Beaverlodge Operation of Eldorado Nuclear Limited (IAEA-PL-565/4) .................................................. 37
   D.D. Bell
   Discussion .......................................................... 46
Radon in uranium mining: Effect of protective controls on uranium resources in South African mines (IAEA-PL-565/9) .................................................. 49
   A.C. Haasbroek, R.S.J. Du Toit
   Discussion .......................................................... 55
   Summary report on Session 1 ......................................... 57

TECHNICAL PROBLEMS OF URANIUM MINE VENTILATION (Session 2)

Ventilation and other problems in controlling radon daughters in uranium mines
   (IAEA-PL-565/5) .................................................. 63
   G.R. Yourt
   Discussion .......................................................... 71
La ventilation dans les mines d’uranium (IAEA-PL-565/3) .................................................. 73
   Y. François, J. Pradel, P. Zettwoog, M. Dumas
   Discussion .......................................................... 107
Mine engineering and ventilation problems unique to the control of radon daughters
   (IAEA-PL-565/7) .................................................. 111
   R.L. Rock
   Discussion .......................................................... 121
   Summary report on Session 2 ......................................... 125

RESEARCH ON MODE OF RADON RELEASE BY DIFFERENT TYPES OF ORE BODY (Session 3)

Radon-222 emanation characteristics of rocks and minerals (IAEA-PL-565/1) .................................................. 129
   P.M.C. Barretto
   Discussion .......................................................... 148
EFFECTS OF RADIOLOGICAL AND WASTE-MANAGEMENT LEGISLATIVE CONTROLS ON URANIUM COSTS AND ORE RESERVES

(Session 1)
EFFECTS OF STRICTER RADIATION EXPOSURE STANDARDS ON URANIUM COSTS AND ORE RESERVES

F.E. McGINLEY
United States Atomic Energy Commission, Grand Junction, Colo., United States of America

Abstract

EFFECTS OF REDUCED RADIATION EXPOSURE STANDARDS ON URANIUM COSTS AND ORE RESERVES.

The radon daughter products found in uranium mine atmospheres have been assumed as the cause of the higher-than-expected incidence of lung cancer among underground uranium miners. Although radon-daughter measurements have been made in United States uranium mines since about 1950, it was not until 1960 that regulatory standards were adopted and systematic monitoring began. The Federal Radiation Council (FRC) in 1967 recommended that occupational exposure be controlled so that no individual miner received an exposure of more than 6 working level months (WLM) in any consecutive 3-month period and an exposure of more than 12 WLM in any consecutive 12-month period. For the next few years there was considerable controversy over the need for a reduced exposure standard. Ultimately, upon recommendation of the FRC, a standard of 4 WLM per year was adopted, effective 1 July 1971. All standards required records to be maintained of individual miners' cumulative radon-daughter exposure.

The effect on domestic uranium mining of compliance with reductions in the exposure standard has been difficult to assess. The economic impact on the cost of production and on ore reserves was studied in 1968 and in 1970 by two firms under Government contracts utilizing information and data provided by various mine operators and the USAEC. The latter study concluded that, to meet the then proposed standard of 4 WLM per year, the industry would need about two years to make the required physical changes in mines and the estimated cost of compliance with the new standard for the different mines would vary from $0 to $0.93 and average $0.24 per pound U₃O₈ in concentrate. The impact on domestic underground ore reserves at $8 per pound U₃O₈ was an estimated reduction of about 20%. However, cost estimates made by the industry showed the reduction in these underground reserves to be 10 to 22% and 5 to 10% on total USA reserves. There are many complexities in a study of this type, particularly when one considers that the actual underground mines in the USA vary considerably in size, production, age, mining methods used, complexity of workings, ventilation schemes employed, and properties of the host rock.

The actual impact of the adoption of the standard of 4 WLM per year on 1 July 1971 has been difficult to evaluate. Certainly, mining costs have increased and many of the small high-cost and marginal mines have shut down but this may reflect the recent market condition as much as the reduction in the exposure standard.

As for the impact of a further reduction in the exposure standard, undoubtedly costs would rise, additional mines would shut down, and reserves mineable by underground methods would decrease significantly. It is hoped that the results of a continuing review of epidemiological data, which showed a decrease in the incidence of lung cancer among uranium miners, will obviate the necessity for recommending a further reduction in the exposure standard.

INTRODUCTION

It is generally agreed that the excess of lung cancer among uranium miners is due, at least in part, to exposure to high concentrations of radon and its daughters and that the risk of lung cancer increases with increasing exposure. In spite of this general agreement, there has been considerable controversy over legislation and regulations to establish standards. During the period 1960 to 1969 there were several public
hearings by various legislative committees, and ultimately the standard was reduced, effective 1 July 1971, to one-third the 1960 standard [1]. Industry and various mining associations voiced strong opposition to the reduced exposure standard as unnecessary for health protection and because of the anticipated impact on the economics of underground mine operation. As with other standards, the difficulty was to determine the balance between risk and benefit which results from the use of atomic energy. The intent of this paper is to review the history of mine radiation exposure standards and the effect of reduced standards on costs and ore reserves.

EVOLUTION OF MINE STANDARDS IN THE UNITED STATES OF AMERICA

The radon daughter products found in uranium mine atmospheres have been assumed as the cause of the higher-than-expected incidence of lung cancer among underground uranium miners. The increased incidence of lung cancer is believed to be induced by the radioactive decay of radon daughters in the respiratory tract. Although uranium-vanadium 'carnotite'-type ore was first mined in the USA as early as 1898, production was limited until about 1935 when the demand for vanadium increased the market for this type ore. However, this production uptrend resulted in no sustained large-scale employment until after the establishment of the first ore-buying schedule by the United States Atomic Energy Commission (USAEC) in 1948. As shown in Table I, employment in underground mines (all privately owned) increased rapidly until about 1960 when it declined as the result of a curtailed Government market for uranium. In recent years, employment has continued to decrease, but projections are that the number of underground uranium miners most certainly will exceed the 1960 level if the anticipated uranium demand for nuclear power production is to be met. The large decrease in the number of mines since 1957 is a reflection of the trend toward larger operations and the shutdown of the very small high-cost and marginal mines in the Uravan Mineral Belt.

<table>
<thead>
<tr>
<th>Year</th>
<th>Mines</th>
<th>Men employed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1954</td>
<td>450</td>
<td>916</td>
</tr>
<tr>
<td>1957</td>
<td>850</td>
<td>2430</td>
</tr>
<tr>
<td>1960</td>
<td>703</td>
<td>4908</td>
</tr>
<tr>
<td>1963</td>
<td>573</td>
<td>3510</td>
</tr>
<tr>
<td>1966</td>
<td>533</td>
<td>2545</td>
</tr>
<tr>
<td>1969</td>
<td>145</td>
<td>2133</td>
</tr>
<tr>
<td>1972</td>
<td>141</td>
<td>1766</td>
</tr>
</tbody>
</table>
Although radon-daughter measurements have been made in the United States uranium mines since about 1950, it was not until 1960 that State agencies and the major mining companies began conducting systematic monitoring in underground mines. In 1959 the United States Public Health Service, and in 1960 the American Standards Association, Inc. (ASA)¹, and the USAEC recommended a standard for uranium mines based on a maximum permissible radon-daughter concentration of one working level² (1 WL) in the mine atmosphere. The ASA standard contained graded action levels that required the determination of the weighted average exposure of workers when any working area showed a working level greater than 1.0 but less than 3.0 [3]. If samples showed working levels greater than 10.0, immediate action was to be taken to reduce the exposure of workers and to correct the conditions. The ASA standard also suggested procedures for mine ventilation and air sampling.

Since the States historically were responsible for mine inspection, the States adopted regulations similar to the above standard. The degree of enforcement varied somewhat among the five western States where uranium was mined but, in general, progress was good in that the average level for the industry was 7 WL in 1957 and by 1966 was down to 2.1 WL [1].

In 1959, by act of Congress (Public Law 86-373), the Federal Radiation Council (FRC) was formed to provide "guidance for all Federal agencies in the formulation of radiation standards and in the establishment and execution of programmes in co-operation with States". On the basis of its studies and deliberations the FRC in September 1967 published the recommendation that no miner be exposed to more than 6 working level months (WLM) in any consecutive 3-month period and to more than 12 WLM in any consecutive 12-month period. Inhalation of air with a concentration of 1 WL for 170 working hours results in an exposure of 1 WLM. Additionally, actual exposures were to be kept as far below these values as practicable and individual exposure records were to be established and maintained [4].

Prior to publication of the FRC report, the Secretary of Labour on 5 May 1967 promulgated a 0.3-WL standard to be enforced under the provisions of the Walsh-Healey Act which applied to Federal supply contracts. Following the announcement of the Department of Labour there was disagreement among the FRC members, various Federal agencies, members of Congress, and industry representatives regarding the basis and necessity for a reduced standard. There were several public hearings, many studies and much debate before the eventual recommendation by the FRC and adoption of the annual exposure standard of 4 WLM as of 1 July 1971 [1]. Since then, the industry has been striving to meet the standard and at a time when costs have been rising and the market for uranium has been depressed.

IMPACT OF REDUCED EXPOSURE STANDARDS ON COSTS

Since all uranium mining in the USA is performed by privately owned companies, actual costs are not available for review. There were, however, two interesting studies of this problem made in 1968 and 1970 for

¹ Later known as USA Standards Institute, now the American National Standards Institute (ANSI).
² Working Level (WL) is defined as any combination of radon daughters in one litre of air that will result in the ultimate emission of $1.3 \times 10^5$ MeV of potential alpha energy.
TABLE II. UNDERGROUND VERSUS OPEN-PIT MINE PRODUCTION [7] (tons U₃O₈)

<table>
<thead>
<tr>
<th>Year</th>
<th>Underground</th>
<th>Open pit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>712</td>
<td>98</td>
</tr>
<tr>
<td>1955</td>
<td>3570</td>
<td>855</td>
</tr>
<tr>
<td>1960</td>
<td>13476</td>
<td>5368</td>
</tr>
<tr>
<td>1965</td>
<td>7424</td>
<td>3014</td>
</tr>
<tr>
<td>1970</td>
<td>6911</td>
<td>5857</td>
</tr>
<tr>
<td>1971</td>
<td>5924</td>
<td>6983</td>
</tr>
<tr>
<td>1972</td>
<td>5588</td>
<td>8079</td>
</tr>
</tbody>
</table>

the FRC under Government contracts and with industry and USAEC cooperation [5, 6]. To determine the impact or effect of a reduced exposure standard it must be recognized that only the underground mines are affected. In the USA, about 40% of current ore production is from such mines whereas open-pit operations account for the remainder. Until 1971, underground mine production of uranium exceeded open-pit production. Table II illustrates the trend in underground versus open-pit mine production in the USA.³

Since about 45% of the known ore reserves at $8 per pound U₃O₈ are at depths of 500 ft or more, one would expect that future underground production would continue at 40 to 45% of the total.

In examining the costs and impact on the industry of going from 1 WL to the proposed 0.3 WL, the study by the Resource Management Corporation (RMC) analysed average mine working levels in relation to the investment, operating and maintenance costs directly attributable to radon control [5]. This approach was necessary because the cost data accumulated by industry only related average mine working levels to control costs. Anyone familiar with uranium mines recognizes that the radon-daughter concentrations can and do vary greatly from area to area, time to time, with climatic conditions and with seasons. An average mine working level is a function of these variations, weighted by the man-hours worked in the various mine areas at the measured radon-daughter concentrations. Thus, in any mine, some miners may work at background concentrations while others may work in areas in excess of the mine average working level.

In regard to costs, historically it has been difficult for the mines to properly allocate costs to radon control because often steps taken to control radon may also serve another purpose. However, with the growing concern in meeting reduced standards the companies now recognize the need for separate reporting of all radon control costs including the establishment and maintenance of individual exposure records.

RMC has analysed the data from three typical small mines in the Uravan Mineral Belt with ore production ranging from 2200 to 36 200 tons/a, and average mine working levels ranging from 0.5 to 3.1. Radon control

³ Tons referred to are short tons unless otherwise specified.
costs in 1968 ranged from $0.57 to $1.47 per ton of ore mined. The study concluded that there would be approximately a 50% increase in ventilation control costs in going from 1.0 WL to 0.3 WL, assuming this were feasible through ventilation efficiency improvements alone.

Similarly, data were analysed from five larger mines which ranged in ore production from 78,000 to 278,000 tons/a. Although the radon control costs ($0.51 to $0.92/ton) for the larger mines were somewhat less than for the small mines the percentage increase required to achieve a 0.3 WL was estimated to be essentially the same.

On an industry-wide basis, RMC has estimated an increase of 50 to 100% in radon control costs for reducing mine average exposures from 1.0 WL to 0.3 WL. The costs on the low side could be realized through more efficient utilization of the existing ventilation systems, those on the high side required major changes or additions to present systems. Both large and small mines were found in each of these groups. Because of the generalized treatment of data these estimates must be used with caution and cannot be applied to any one mine.

The study in 1970 by Arthur D. Little, Inc. (ADL) was more comprehensive than the earlier described study in that data from 26 mines were analysed [6]. Additionally, ADL examined the alternatives of a 12-, 8- and 4-WLM annual exposure and assessed the economic effects on the ore-producing industry, the nuclear power industry, the consumer of electricity and on communities dependent on uranium production. The 26 mines selected for the study represented 21% of the total number of mines, 77% of the total ore production, and 74% of the number of workers employed in underground mines. They included new, middle-aged and old mines; small, medium and large producers, and mines for uranium alone and those mined for a co-product (vanadium). The cost data were for conditions prevailing in March 1970.

The ADL study concluded that to meet the then proposed standard of 4 WLM per year the domestic industry would need about two years to make the required physical changes in the mines. The estimated cost of compliance with the new standard for the different mines was estimated, on an incremental basis, to vary from $0 to $0.93 and average $0.24 per pound U$_3$O$_8$ in concentrate. This average increase in cost is about $1.00 per ton of ore mined, based on the average U$_3$O$_8$ grade of ore processed in the USA.

An estimate made by the industry for the same 26 mines showed that the cost of compliance with the standard of 4 WLM per year would be considerably greater than that estimated by ADL and would range from $0 to $1.75 per pound U$_3$O$_8$ and average about $0.70. Using the same basis as above, the industry-calculated average cost was about $2.80 per ton or almost three times the ADL projection. The disagreement in estimates for individual mines resulted primarily from the assumptions made regarding 'cease work' orders. ADL assumed that the mines would continue to be operated so that the frequency of such orders would remain about the same as in 1970. The industry assumed that there would be an increased frequency of 'cease work' orders, and since working areas would be closed until the high radiation levels were brought under control it would be necessary to move miners elsewhere, which would result in a decrease in productivity. Another area of disagreement in cost estimates was the capital required for vent holes and ventilation equipment. The
industry estimated greater costs and assumed different amortization than ADL.

In summary, these studies showed that, to comply with a reduction in the mine radiation exposure standard from 12 WLM to 4 WLM per year, the industry probably would experience an average increase in mining costs ranging from $0.24 to $0.70 per pound U₃O₈ in concentrate, depending on the assumptions. There are many complexities in studies of this type because mines vary considerably in size, production, age, mining methods used, complexity of workings, ventilation schemes employed, and properties of the host rock.

The actual impact of the reduction of the exposure standard to 4 WLM per year on underground mining costs has been difficult to assess on an industry-wide basis. Undoubtedly radon control costs have risen as evidenced by the increased drilling of vent holes and the purchase and use of electrostatic precipitators by the largest mining company in the Uravan Mineral Belt [8]. During this same period the number of operating mines has decreased significantly (about 25%). Many of the mines which were shut down could not stand the added capital expenditures and increased operating costs for radon control. However, this situation may reflect the recent market condition as much as the reduction of the exposure standard.

IMPACT OF REDUCED EXPOSURE STANDARDS ON ORE RESERVES

Before discussing the impact on ore reserves, some understanding of the calculation method of ore reserves is desirable. Therefore, attached as Appendix A is a "General description of AEC reserve estimates". It will be noted that any increase in cost resulting from a reduced radiation exposure standard has the effect of reducing the cut-off grade of the deposit and thereby decreasing the economically exploitably tonnage of the deposit. Since the ore reserves for each deposit are calculated individually on the basis of company-provided data it would be difficult and time-consuming to assess the impact of a reduced radiation exposure standard except in a very general manner. In the previously mentioned 1970 study, ADL estimated that the underground ore reserves at $8 per pound U₃O₈ would be reduced by about 2% if the exposure standard were reduced from 12 WLM to 4 WLM per year. However, the cost estimates made by the industry showed the reduction in the $8 reserves minable by underground methods to be 10 to 22%, which is 5 to 10% of the total USA $8 reserves. Therefore, one might conclude that the total known USA ore reserves at $8 per pound U₃O₈ could have been decreased by up to 10% by the reduction in the exposure standard from 12 WLM to 4 WLM. The impact would be somewhat less on the ore reserves of $10, $15 and $30 per pound U₃O₈ but this has not been evaluated.

IMPACT OF A LOWER STANDARD

As for the impact of a further reduction of the exposure standard, one could be sure that costs would rise significantly and reserves would
decrease depending, of course, on the exposure level selected. The industry has argued that many mines could not economically meet a standard of 4 WLM per year, and experience has shown this to be true. It appears that further substantial reduction, such as to 0.1 WL, might eliminate conventional underground mining except in the most ideal situations. It is hoped that the results of a continuing review of epidemiological data, which showed a decrease in the incidence of lung cancer among uranium miners, will obviate the necessity for recommending a further reduction in the exposure standard [9]. Whether the decreased incidence of lung cancer since 1968 is a reflection of improved ventilation in the mines or of a decrease in cigarette smoking among miners is not known. In any case it is interesting to note that Saccomanno [9] reports that of the 160 cases of tissue-proven lung cancer among the uranium miners only one was a non-cigarette smoker. This possible synergistic relationship between smoking and exposure to radon daughters prompted some mine operators several years ago to encourage miners to stop smoking. In 1969, the Department of the Interior published a standard prohibiting smoking where uranium is mined [10].

APPENDIX A

GENERAL DESCRIPTION OF AEC RESERVE ESTIMATES [7]

Estimates of United States uranium ore reserves represent the amount of uranium that could be exploited at maximum forward costs of $8, $10, $15 and $30 per pound U₃O₈ respectively. Such reserves, computed by consistent methods for uniformity, are derived from data provided by the private uranium companies. The fact that the reserves may be considered by the AEC as exploitable at a stated maximum forward cost does not imply a judgement or a prediction by the AEC that such reserves would necessarily be available at a similar market price.

Briefly, the estimating process for ore reserves consists of the following steps:

1. Determination of the 'cut-off' to define the lowest grade (in per cent U₃O₈) of material that can be mined from a deposit at a minimum thickness where the total operating cost per pound of recoverable U₃O₈ in such material is equal to the chosen maximum forward cost per pound. The cut-off grade is determined by the following formula:

   \[
   \text{Cut-off grade} = \frac{\text{Cost of mining, hauling, royalty and milling/ton of ore}}{\text{Maximum forward cost/lb U₃O₈} \times \text{mill recovery} \times 20}
   \]

2. Estimation of the mineralized material in the deposit that meets or exceeds the cut-off grade and thickness criteria, expressed in tons and average grade of U₃O₈.

3. Application of all forward costs, operating and capital, to the mineralized material derived in Step 2.

4. If the cost per pound U₃O₈ derived in Step 3 is less than the chosen maximum forward cost per pound, then the material is considered to be a reserve.
Property acquisition costs, finding costs, and other past capital costs are considered sunk costs. Sunk costs, cost of money, money accumulation for replacing the ore reserve, and a profit are not used in AEC cut-off determination or in the economic evaluation of an ore reserve. These factors must be considered by each company individually and are integrated into their negotiated prices for uranium.

The computed ore reserves at $8, $10, $15 and $30 per pound U₃O₈ each successively include all the reserves in the lesser cost categories.

REFERENCES


DISCUSSION

A. GOODWIN: You imply that the reason why 25% of the uranium mines have closed since the new standards came into effect is solely that radiation controls are uneconomical. Are there no other factors in addition to radiation controls which may have contributed to these mines closing?

F.E. McGINLEY (Chairman): I do qualify that statement in my abstract when I say that mining costs have certainly increased and many small, high-cost and marginal mines have shut down; but this may reflect the recent market conditions as much as the reduction in the exposure standard.

J.A. PATTERSON: In your paper you pointed to a difference of opinion during the preparation of the ADL study between the industry and ADL workers as to how the standard was to be enforced. I think this is an important matter, and I think it might be very fruitful if there were some discussion here, particularly from the Bureau of Mines people, as to the implications of changing from a concentration standard that, in effect, was concerned with working-level concentrations of radon daughters to an exposure standard of four working-level months per year. The implications of its impact on the mine operator are important. In the first instance actions were taken when radon daughter levels were exceeded in a working area; these levels could be measured and corrective action taken immediately.
In the revised standard, the actions are based more on the accumulated exposure record of a particular worker. Obviously there are a number of ways in which the latter standard can be enforced. What would be the impact on the mine operator and hence on the cost which he will experience? It is not too clear, in my mind, exactly how the current standard is really being enforced.

F.E. McGINLEY (Chairman): Thank you Mr. Patterson, I think that is a very appropriate subject and I would like to ask Mr. Rock, Mr. Goodwin or Mr. Richardson of the US Bureau of Mines to comment and to explain the situation in the USA today, particularly in regard to how the individual States operate and what conformity or inconsistencies there might be between the States as far as inspections and cease-work orders are concerned.

A. GOODWIN: Probably I should say just a little about the regulations, what they were and what they are now. Briefly, the regulations that were in force included both an exposure standard and a concentration standard. The exposure standard required that no person be exposed to greater than six working-level months in any period of three consecutive months. The concentration standard required that, where concentrations exceeded one working level but were not greater than two working levels, immediate corrective action be taken to reduce the levels to below one working level. When concentrations exceeded two working levels, immediate action was required to reduce the levels and, in addition, all persons not needed to accomplish this reduction should be withdrawn from the area. This latter concentration standard still remains in effect. But the standard on radiation exposure has been superseded by one which states that no employee shall be permitted an annual exposure in excess of four working-level months. Needless to say, the concentration standard is the one that mine inspectors most frequently use during an inspection. Concentration is something that they can measure immediately while at the mine and take appropriate enforcement action. In order to enforce the standard of four working-level months per year, the mine inspector must review the records that the mine operators are required to keep. It is impossible of course to ensure that these records are properly kept and are accurately maintained. Exposure records are necessarily maintained by the mine operators and so a mine inspector can only qualitatively determine whether the operator is keeping these records in a correct manner, but he cannot verify the actual data used to compute exposure. According to the operators' records, only six persons in United States uranium mines were exposed to greater than four working-level months in the calendar year 1972. The highest exposure of these six persons was slightly over five working-level months. We do not condone exposures over four working-level months; however, there is really very little that can be done after persons have been found to exceed this limit. Most inspector action is taken on the basis of concentration measurements, and the present concentration standard, which is the one I spoke of previously, is not consistent with the exposure limit of four working-level months per year. We are planning to change this standard.

D.D. BELL: As I understand it, the basic measuring equipment is still concerned with the concentration. The mine operator records the concentration periodically, and then the time down the mine of the miner is multiplied by that.

A. GOODWIN: That is right. We have under development a number of dosimeters, and here we must give credit to the US Atomic Energy Com-
mission laboratories who have done most of the work. We are at present testing a dosimeter that was developed by the Health and Safety Laboratories in New York. Maybe we shall have something that works and maybe we shall not. There are a number of difficulties with dosimeters so we do not feel that they are the perfect solution. But we would prefer dosimeters to an elaborate method of record-keeping, and I expect they might even reduce some of the costs even though the dosimeters will be quite expensive.

D.D. BELL: What is the frequency of testing?

A. GOODWIN: Unfortunately our regulations are deficient in this regard too. We recommend monitoring at least once per week in each working area and most United States mine operators conform to this recommendation. There are, however, a number of operators of small mines that depend on State and Federal inspection personnel to make measurements. These operators do not have the equipment nor the trained people to make the measurements and, therefore, the concentrations are generally not determined more frequently than once per month.

J.A. PATTERSON: If in fact the exposure standards are being met, why do you say that the cease-work concentration level is not appropriate?

A. GOODWIN: There are really two standards; one is the standard that limits the concentration which, as I said before, is used most by inspectors and the other is the exposure standard. We rely on the mine operator's records to determine compliance with the exposure standard. However, when reviewing concentration data taken during inspections for the latter half of 1972, somewhat less than 50% of all miners observed during the day of an inspection were working in time-weighted average concentrations that would result in an annual exposure of less than four working-level months. Therefore, if these conditions continued day in and day out, the exposures calculated by the mine operator should show only 50% compliance. We have even detected levels as high as 50 working levels and these concentrations never appeared on operators' exposure records. But at 50 working levels one can get four working-level months in approximately two shifts. So you see, we have reason for some scepticism with respect to the exposure records of operators and I think this is why we would like to lower the concentration standards.

R.H. KENNEDY: I wonder if you are able to say what concentration standard would, in your opinion, be necessary to assure consistently meeting the 4 WLM/a exposure standard.

A. GOODWIN: The concentration we are recommending to our Advisory Committee is one working level. As such, one working level represents a limit to the radon daughter concentration which should not be exceeded. One working level is approximately three times the time-weighted average that would result in a 4 WLM/a exposure. This is consistent with the so-called excursion limits which we allow for other contaminants such as dust and some toxic gases.

F.E. McGINLEY (Chairman): By 'taking action', do you mean you would require the removal of miners from an area whenever the working level exceeded one?

A. GOODWIN: Our Federal law is written to require that a mine inspector issue a notice of non-compliance when he observes a violation of a standard. When he issues such notice, he must also determine a reasonable time for compliance with the notice. Of course, if there is a condition which presents an imminent danger, he must issue an order to withdraw the employees from
such an area. However, radiation is not of an 'imminent danger' nature, in general, and so nearly all non-compliance notices require corrective action to be taken. A reasonable time for compliance depends not only on the type of hazard but on what will happen to the miners if they continue working under the existing conditions. Therefore, a 'reasonable time' depends on the radon daughter concentration as well as the amount of corrective action required. Our guidance to inspectors may be, for example, that between one and two working levels the mine operator be allowed up to one week to comply. If the operator does not comply within the time limit, then the inspector may issue an order requiring withdrawal of the miners until compliance is achieved, or he may extend the notice if the thinks the condition is warranted. If concentrations get up to ten working levels or so, we would require more immediate response.

G.F. TAPE: At the present time in many undertakings in the various competitive forms of energy supply, and owing to the impact of environmental problems, we tend to have to take into consideration escalation, inflation and so on, in various components, when looking at future costs. Now, certain component costs may be rising very rapidly, and therefore something like radon protection costs, for example, might be lost in the 'noise' of the escalation in other areas. Can you say whether the normal safety factors, or just the cost of labour for miners, might compare with the implemental costs on changing safety standards with respect to radon radiation?

F.E. McGINLEY (Chairman): I have noticed that within the industry, although there have been complaints for many years about the increased cost of meeting improved standards, and certainly these costs have been real, there has been a general improvement in efficiency of operation, so that the increased costs tend to be offset by other cost savings. Generally, stricter standards prompt closer examination of the total operation and improvements in working result that perhaps would not have been realized otherwise.

J.A. PATTERSON: I would say that the other factors that affect the price of uranium have exerted a far greater influence on costs, and these will, in my opinion, be more than the increased costs of radon control under the standards that we are now talking about. We are on a diminishing-returns situation with radon control, but I presume that we have now reached a standard with which most people are reasonably satisfied. Labour costs and inflation are certainly factors which will tend to rise and to be very significant. Another factor will be the need to discover more uranium reserves to meet future requirements; this cost will be higher than previously.

D.D. BELL: With respect to tightening standards to less than 4 WLM/a, which is what you are speaking about now, essentially the only way to comply is by transferring a higher volume of air through the mine. You induce an awful lot of problems for yourself and for the operators by doing this.

C. PALMITER: I am interested in what you said, Mr. Bell; are there other means by which we can protect the miner, for example, by providing enclosed breathing units or something similar rather than relying strictly on ventilation? I do believe you may be reaching a point where you are going to be blowing miners over if you drive any more air through those drifts!

D.D. BELL: Enclosed breathing units also create problems in themselves by affecting the comfort and productivity of the workers. It is pretty difficult, you know, to work in closed systems— in masks or anything else.
J. CAMERON: As regards cigarette smoking and the cancer hazard, is there a comparison with any other population group, in other words, with cigarette smokers who are not uranium miners? Is there a significantly increased relationship because of synergism of the two factors, the cigarette smoking and the uranium mining; has this been proven?

F.E. McGINLEY (Chairman): I think it has been proven to Dr. Geno Saccomanno's satisfaction, although I am not sure that other medical doctors agree with him. Perhaps Mr. Palmiter could speak to this because I am sure that this is something the Federal Radiation Council considered quite thoroughly, together with the National Academy of Sciences.

C. PALMITER: I do not remember the details but, at the time the Academy's study was being conducted, we felt that cigarette smoking was certainly a cosynergistic element. But the Public Health Service studies, I believe, were not conclusive. We did not have a comparison group, not inhaling radon but smoking.
INCIDENCE DES NORMES DE RADIOPROTECTION SUR LE MARCHE DE L'URANIUM

Y. FRANÇOIS, J. PRADEL, P. ZETTWOOG
CEA, Centre d'études nucléaires
de Fontenay-aux-Roses,
Département de protection,
Fontenay-aux-Roses,
France

Abstract—Résumé

THE EFFECT OF RADIOLOGICAL PROTECTION STANDARDS ON THE URANIUM MARKET.

On the basis of concrete results obtained in the CEA's uranium mines over a period of 15 years, the authors determine in the first part of the paper to what extent the costs of radiological protection, which are based on current EURATOM standards, affect the price of uranium. The principles on which radiological protection is organized in the CEA mines are mentioned (independence of the radiological protection service from the mining services, constant presence in the workings of radiological protection officers, multiple sampling). Emphasis is placed on the precautions which have to be taken in order to ensure that radioactivity measurements are representative despite the extreme complexity and the variability of conditions in the workings and so that not just lip service is paid to the standards. A description is given of the way in which the operation of the ventilation system is varied on the basis of radioactivity measurements as the workings are extended. The authors reach the conclusion that in the CEA mines, where the uranium content in the ores frequently exceeds one per cent, it is possible to ensure that the current standard \(3 \times 10^{-10} \text{Ci Rn/litre},\) the equilibrium factor for radon and its daughters being taken as 0.5) is actually adhered to and that nevertheless the cost of radiological protection remains marginal.

In the second part of the paper the possible effects of increasing the stringency of the standards are examined. The considerations are based on several thousands of measurements carried out in various workings and galleries. It is shown that the correlation between radon concentration and ore content is weak, which rules out the possibility of being able to calculate in a simple way what the reduction in uranium reserves would be if it were necessary to reduce the acceptable concentrations in the air of the workings. It is pointed out that the state of equilibrium of radon daughters in the workings is of the order of 0.2 rather than the 0.5 assumed in the standard. On this basis the mean level of actual exposure, in total alpha energy, is of the order of 20% of the value \(1.3 \times 10^5 \text{ MeV/litre},\) the level of the most highly exposed worker being 80% of that value. In addition, it is shown that with simple improvements to the design of the ventilation circuits and elementary precautions it is often possible to "rejuvenate" the radon in the workings and influence still further the state of equilibrium of the daughters. Finally, preliminary results obtained in the experimental mine at La Crouzille indicate that the radon concentration can be further influenced by subjecting the mine to an overpressure. In these circumstances it would appear that the careful application of existing methods should make it possible to tolerate a moderate increase in the rigour of the standards. The sensitivity of the cost of radiological protection to various factors is investigated.

It is concluded that the introduction of slightly stricter standards — by a factor of three, for example — would in the short term have only a slight effect on the price of uranium from existing mines, and this effect would undoubtedly be absorbed in future mines, provided that operations were geared to these new standards from the outset. In the long term the uranium market would not be affected and the effect on world reserves would be negligible. On the other hand, stricter standards going beyond a certain threshold might make mining impossible and reduce world reserves to the amounts obtainable by quarrying.
INCIDENCE DES NORMES DE RADIOPROTECTION SUR LE MARCHE DE L'URANIUM.

Dans une première partie, les auteurs établissent, à partir des résultats obtenus concrètement dans les mines d'uranium du Commissariat à l'énergie atomique depuis quinze ans, quelle est l'incidence du coût de la radioprotection qui est basée sur les normes EURATOM actuelles, sur le prix de revient de l'uranium. Les principes à partir desquels la radioprotection est organisée dans les mines du CEA sont rappelés. On insiste sur les précautions à prendre pour que les mesures de radioactivité effectuées soient représentatives malgré l'extrême complexité et la variabilité des situations dans les chantiers et donc pour que le respect des normes ne soit pas un vain mot. La manière dont, d'après les mesures de radioactivité, on conduit les opérations d'aérage au fur et à mesure de l'avancement des chantiers est décrite. On conclut que dans les mines du CEA, où l'on rencontre des teneurs en uranium dans les minerais dépassant fréquemment un pour cent, on peut assurer que la norme actuelle (3 \times 10^{-10} Ci/\text{m}^3, le facteur d'équilibre du radon et de ses descendants étant supposé égal à 0,5) est effectivement respectée, et que cependant le coût correspondant de la radioprotection reste marginal.

Dans une deuxième partie, les auteurs examinent les effets que pourraient avoir une augmentation de la sévreté des normes. En se basant sur plusieurs milliers de mesures effectuées dans les divers chantiers et galeries, ils démontrent que la corrélation entre la concentration en radon et la teneur en minerai est faible, ce qui exclut que l'on puisse calculer simplement quelle serait la réduction des réserves d'uranium si on devait réduire les concentrations acceptables dans l'air des chantiers. Ils font ressortir que l'état d'équilibre des descendants du radon dans les chantiers est de l'ordre de 0,2 au lieu de 0,5 admis dans la norme. Dans ces conditions, le niveau moyen d'exposition réel, en énergie alpha totale, est de l'ordre de 20% de la valeur 1,3 \times 10^{15} \text{MeV o/l}, le niveau de l'agent le plus exposé étant de 80% de la même valeur. De plus, on montre que des améliorations simples apportées dans la conception des circuits d'aérage et des précautions élémentaires permettent souvent de «rajeunir» le radon des chantiers, et de gagner un nouveau facteur sur l'état d'équilibre des descendants. Enfin, les auteurs indiquent que des résultats préliminaires obtenus dans la mine expérimentale de La Crouzille montrent que la mise en surpression de la mine permet de gagner un nouveau facteur sur la concentration en radon. Dans ces conditions, il apparaît que la mise en œuvre soignée de procédés déjà connus permettrait de faire face à une augmentation modérée de la sévreté des normes. La sensibilité du prix de revient de la radioprotection à différents facteurs est étudiée.

Les auteurs concluent que la mise en œuvre de normes légèrement plus strictes, d'un facteur 3 par exemple, aurait à court terme une incidence faible sur le prix de revient de l'uranium extrait des mines actuelles; cette incidence serait sans aucun doute amortie pour les mines futures dans la mesure où l'exploitation serait déjà le début conçue pour les nouvelles normes. À long terme, le marché de l'uranium ne serait pas perturbé et l'effet sur le volume des réserves mondiales resterait négligeable. Par contre, des normes plus sévères, au-delà d'un certain seuil, risqueraient de rendre l'exploitation impossible et donc, de réduire l'état des réserves mondiales à ce qui est exploitable en carrière.

INTRODUCTION

Dans une première partie, on établit quelle est la part, dans le coût de production de l'uranium, du coût de la radioprotection, que notre Service assure dans les mines d'uranium du CEA en se conformant aux normes EURATOM. On se base sur l'expérience acquise au cours de 16 ans de contrôles quotidiens effectués dans les chantiers et les galeries. Dans une deuxième partie, on examine quelle serait l'incidence d'une augmentation de la sévreté des normes sur le coût de production de l'uranium, et à partir d'hypothèses simplificatrices sur l'évolution future des lois d'offre et de demande qui régissent le marché de l'uranium, on estime quelle en serait la conséquence sur le volume des réserves économiquement exploitables.
1. COUT DE LA RADIOPROTECTION

1.1. Données relatives aux mines du CEA

Les gisements d'uranium actuellement exploités en France, à l'exception du petit gisement sédimentaire de St-Pierre du Cantal, se présentent sous la forme de filons fortement pentés, ou d'amas dans des granites. Ils sont donc assez semblables à des gisements métallifères classiques.

Le CEA est le principal producteur français puisque, en 1972, sur une production métropolitaine de 1420 t d'uranium, sa part a été de 1320 t.

Les minerais exploités ont des teneurs relativement basses, allant de un à quelques kilogrammes de métal à la tonne.

Le personnel directement affecté au contrôle radiologique correspond à environ 3% de l'effectif « fond » des divisions minières et à 1,5% de l'effectif global de ces divisions.

Le total des réserves démontrées et en perspective au 1er juillet 1972 était de 39 400 t d'uranium, en se basant sur un cours voisin de 100 FF/kg d'uranium contenu dans les concentrés marchands, ce qui correspond à 8,5 $/lb de U₃O₈.

Le tableau I rassemble les renseignements relatifs à chacune des divisions minières.

TABLEAU I. RENSEIGNEMENTS RELATIFS AUX DIVISIONS MINIÈRES (année 1972)

<table>
<thead>
<tr>
<th>Divisions minières</th>
<th>Tonnage de minerai extrait (t)</th>
<th>Uranium contenu (t)</th>
<th>Teneur (%)</th>
<th>Effectif «fond» contrôlé</th>
<th>Effectif du Groupe radioprotection</th>
<th>Nombre de prélèvements radon</th>
<th>Réserves d'uranium (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>96348</td>
<td>262,7</td>
<td>3,77</td>
<td>265</td>
<td>9</td>
<td>15 812</td>
<td>16 900</td>
</tr>
<tr>
<td>B</td>
<td>116852</td>
<td>267,1</td>
<td>2,29</td>
<td>204</td>
<td>8</td>
<td>16 380</td>
<td>6 900</td>
</tr>
<tr>
<td>C</td>
<td>81203</td>
<td>295</td>
<td>3,63</td>
<td>152</td>
<td>4</td>
<td>6 529</td>
<td>2 900</td>
</tr>
<tr>
<td>D</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12 700</td>
</tr>
<tr>
<td>Ensemble des divisions</td>
<td>294 403</td>
<td>924,8</td>
<td>3,1</td>
<td>621</td>
<td>21</td>
<td>36 721</td>
<td>39 400</td>
</tr>
</tbody>
</table>

a Uranium extrait en mine hors carrière et lixiviation.

1.2. Organisation de la radioprotection

1.2.1. Principes essentiels

Nous avons attaché une importance particulière à ce que les principes ci-dessous soient respectés:
a) Indépendance hiérarchique du Groupe de radioprotection vis-à-vis des responsables de l'exploitation, la bonne définition des responsabilités respectives de chaque partie assurant une excellente collaboration entre celles-ci;

b) Présence permanente sur les chantiers des agents de surveillance, afin d'éviter la lente détérioration de la qualité des circuits de ventilation;

c) Multiplicité du nombre des prélèvements afin que, malgré les fluctuations considérables qui peuvent apparaître dans le temps sur les concentrations en radon, on obtienne une représentation statistiquement valable de la situation réelle dans la mine.

1.2.2. Normes pratiques

Nous nous conformons aux normes suivantes:

a) Radon: L'activité $\alpha$ du radon gaz ne doit pas dépasser $6 \cdot 10^{-10}$ Ci/l sur les lieux de travail. Cette valeur est déduite de la norme EURATOM $3 \cdot 10^{-10}$ Ci/l pour le radon en équilibre avec ses descendants en prenant un facteur 2 pour tenir compte du déséquilibre;

b) Poussières à vie longue: L'activité $\alpha$ ne doit pas dépasser $35 \cdot 10^{-15}$ Ci/l sur les lieux de travail;

c) Irradiation externe: Elle doit rester
   — inférieure à 5 rem/an pour l'organisme entier
   — inférieure à 15 rem/an pour le poumon;

d) Cumul des risques: Alors que la norme sur l'irradiation $\gamma$ est relative à la dose reçue, les deux autres définissent des niveaux limites de concentration à ne pas dépasser sur les lieux de travail. En France, on fait correspondre aux concentrations mesurées en radon et en poussières, des quantités inhalées individuelles qui tiennent compte du temps passé par chaque agent sur les différents chantiers. On s'impose alors de respecter la condition supplémentaire suivante: la somme des 2 premiers risques, représentés par la fraction de la quantité inhalée à la quantité qui aurait été inhalée par un agent travaillant 264 jours de 8 heures à la concentration maximale, et du risque $\gamma$ exprimé en fraction de la dose maximale admissible, doit rester inférieure à 1.

1.2.3. Méthodes de mesures

a) Radon: On préleve dans un flacon de $125 \text{ cm}^3$ tapissé intérieurement de sulfure de zinc, le radon que l'on débarrasse préalablement de ses descendants en lui faisant traverser un filtre en papier. Au bout de trois heures, les descendants du radon apparus dans le flacon sont en équilibre avec le radon gaz, et la mesure de l'activité $\alpha$ totale par un ensemble de comptage permet de déterminer aisément la concentration en radon au point de prélèvement;

b) Poussières: On a adopté un matériel robuste et d'utilisation aisée, constitué par un filtre de prélèvement de $110 \text{ mm}$ de diamètre, placé dans un porte-filtre associé à une trompe à air comprimé. Le débit est réglé à $250 \text{ l/min}$ et le prélèvement dure de 10 à 20 min. L'activité $\alpha$ du filtre est mesurée 3 j après, au moyen d'un passeur d'échantillons;

c) Irradiation externe: Chaque agent est muni d'un film individuel, échangé tous les mois. Dans les chantiers considérés comme minéralisés,
un premier contrôle est effectué à l'aide d'un radiomètre équipé d'un compteur Geiger. Si l'intensité d'irradiation est supérieure à 2,5 mrem/h, un contrôle par stylo électromètre est organisé.

1.2.4. Calcul des doses individuelles reçues

Le groupe local de surveillance est chargé d'établir pour chaque agent une fiche annuelle où sont consignées les doses reçues chaque mois pour chacun des trois risques. En ce qui concerne l'irradiation γ, la lecture du film donne directement la dose reçue. Pour le radon et les poussières, il faut faire correspondre aux mesures de concentrations sur les lieux de travail les doses reçues individuellement. Pour ce faire, on utilise les fiches de pointage sur lesquelles figure le nombre de postes effectués dans les différents chantiers par chaque agent. Ces calculs sont effectués par mécanographie.

Le règlement prévoit que les prélèvements doivent être effectués au moins une fois par mois pour les poussières, et une fois par semaine pour le radon, dans tous les chantiers et en certains points des galeries. Cette fréquence doit être triplée s'il y a lieu de craindre une augmentation de la teneur en radon. Un contrôle est effectué à chaque changement d'aération. Dans les chantiers en activité, on effectue trois prélèvements par semaine: pendant la foration, après le tir au moment du retour des ouvriers, et pendant le chargement des produits.

En 1972, 36 721 prélèvements de radon et 8 976 prélèvements de poussières ont été faits.

1.2.5. Contrôle des débits d'aération

La concentration en radon étant liée à la qualité de l'aération, le groupe local de surveillance est également chargé de contrôler les débits d'air dans les chantiers. Il mesure également les paramètres qui déterminent la circulation de l'air dans la mine (résistances, dépressions, débit des ventilateurs et ouvrages d'aération primaire) et établit ainsi le schéma d'aération. Ces données sont introduites dans un ordinateur qui peut traiter de façon optimale les problèmes d'aération posés au fur et à mesure de l'avancement de l'exploitation.

1.2.6. Liaisons avec les responsables de l'exploitation

Le responsable local de la radioprotection communique régulièrement les résultats des contrôles aux responsables de l'exploitation.

En cas d'augmentation anormale de la concentration dans un chantier, le groupe local peut suggérer des améliorations d'aération à l'ingénieur chargé de l'exploitation, à qui il appartient de prescrire aux différents ingénieurs, chefs de sièges, les modifications qui lui semblent acceptables du point de vue de l'exploitation.

Au vu des résultats relatifs aux doses reçues par chaque agent, les chefs de siège fixent les affectations sur les chantiers pour que les normes soient respectées.
TABLEAU II. REPARTITION DU PERSONNEL SUR LA BASE DE LA NORME CUMULEE (année 1972)

<table>
<thead>
<tr>
<th>Divisions minières</th>
<th>Cumul au niveau du poumon (Radon + poussières à vie longue + Irradiation externe)</th>
<th>Effectifs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0,11</td>
</tr>
<tr>
<td>A</td>
<td>29</td>
<td>59</td>
</tr>
<tr>
<td>B</td>
<td>24</td>
<td>34</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>Ensemble des divisions</td>
<td>55</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>8,9%</td>
<td>17,7%</td>
</tr>
</tbody>
</table>

TABLEAU III. POURCENTAGE DE CHAQUE RISQUE DANS LE CUMUL DES DOSES

<table>
<thead>
<tr>
<th>Divisions minières</th>
<th>Contributions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>du radon</td>
</tr>
<tr>
<td>A</td>
<td>67</td>
</tr>
<tr>
<td>B</td>
<td>62</td>
</tr>
<tr>
<td>C</td>
<td>68</td>
</tr>
<tr>
<td>Ensemble des divisions</td>
<td>68</td>
</tr>
</tbody>
</table>

TABLEAU IV. RESULTATS DE MESURES SIMULTANEEES

<table>
<thead>
<tr>
<th>Opérations</th>
<th>Nombre de mesures simultanées</th>
<th>Valeur moyenne des résultats</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Activité du radon (6·10^-10 Ci/l)</td>
<td>Energie des descendants (1,3·10^5 MeV α/1)</td>
</tr>
<tr>
<td>Foration</td>
<td>91</td>
<td>0,31</td>
</tr>
<tr>
<td>Après tir</td>
<td>101</td>
<td>0,37</td>
</tr>
<tr>
<td>Raclage</td>
<td>102</td>
<td>0,37</td>
</tr>
<tr>
<td>Chargement</td>
<td>12</td>
<td>0,40</td>
</tr>
<tr>
<td>Boisage</td>
<td>32</td>
<td>0,40</td>
</tr>
<tr>
<td></td>
<td>338</td>
<td>0,36</td>
</tr>
</tbody>
</table>
1.3. Résultats de la radioprotection

1.3.1. Cas des mines

Le tableau II, qui correspond à l'année 1972, montre que dans les mines du CEA, où l'on rencontre en général des teneurs allant de 1 à 5% et parfois supérieures à 1%, la norme pratique française, qui cumule les effets du radon ($6 \times 10^{-10}$ Ci Rn/l), des poussières à vie longue ($35 \times 10^{-15}$ Ci/l) et de l'irradiation externe au niveau du poumon (15 rem/an), est effectivement respectée.

Les agents les plus exposés en 1972 étaient à moins de 90% de la norme, et 82% des agents étaient à moins de 50%. Les résultats étaient du même ordre au cours des années précédentes. On notera que le risque radon représentait 66% du risque total au niveau du poumon et l'irradiation externe 20% (tableau III). Il en résulte que si les efforts d'amélioration doivent porter en priorité sur le risque radon, les deux autres ne sont pas non plus à sous-estimer.

On a représenté sur la figure 1 l'histogramme et la fréquence cumulée des doses reçues pour le risque «radon» seul, pour l'ensemble des divisions en 1972:

- la valeur médiane des doses reçues est de $0,21 \ (6 \times 10^{-10})$ Ci/l;
- la valeur moyenne des doses reçues est de $0,23 \ (6 \times 10^{-10})$ Ci/l.

Les produits radioactifs contenus dans l'air de la mine et inhalés par les travailleurs peuvent représenter des dangers très variables. On admet que le radon représente, dans la mesure où il ne se dissout pas dans les tissus et est rejeté à chaque expiration, un risque faible. Les descendants du radon sont plus dangereux parce qu'ils sont captés par les voies respiratoires et les bronches; l'efficacité de captation dépend de la taille et de la charge des particules qui ont fixé les atomes radioactifs. Il apparaît que les biologistes ne se sont pas encore mis d'accord sur le choix du paramètre le plus représentatif du risque représenté par le radon et ses descendants. Certains pays, les États-Unis en particulier, ont préféré mesurer l'énergie α totale correspondant à la désintégration des descendants du radon qui est exprimée dans l'unité $1,3 \times 10^5$ MeV α/l, appelée «Working Level (WL)>>.

Pour pouvoir effectuer des comparaisons et posséder des données plus complètes, nous avons jugé prudent de mesurer également le niveau d'énergie α dans nos mines.

Le tableau IV montre les résultats de 338 mesures simultanées de l'activité du radon et de l'énergie α de ses descendants, effectuées en 1972 dans les chantiers d'une division minière.

La comparaison des 2 colonnes montre que le radon est très loin de l'équilibre dans nos mines, ce qui est cohérent avec le fait que le temps de transit de l'air primaire est de l'ordre de 10 minutes.

Le facteur d'équilibre $f_{ABC}$ est le rapport de l'énergie α des descendants du radon effectivement présents à celle qui existerait si les descendants du radon étaient à l'équilibre. Ce facteur est représentatif de l'âge du radon.

L'énergie α de $10^{-10}$ Ci/l de radon en équilibre avec ses descendants est $1,3 \times 10^5$ MeV. Le facteur d'équilibre $f_{ABC}$ de nos chantiers est ainsi en moyenne de $0,24/(0,36 \times 6) = 0,11$.

Ces résultats permettent de calculer les doses reçues selon l'unité en usage aux États-Unis, le «Working Level Month (WLM)>>, qui est la
TABLEAU V. SURVEILLANCE DES MINES (année 1972)

<table>
<thead>
<tr>
<th>Effectifs contrôlés</th>
<th>Division A 265</th>
<th>Division B 204</th>
<th>Division C 152</th>
<th>Totaux 621</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Effectifs Steppa</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ingénieur</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Agent de maîtrise</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Préleveurs</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td><strong>Nombre de prélèvements</strong></td>
<td>13812</td>
<td>16380</td>
<td>6529</td>
<td>36721</td>
</tr>
<tr>
<td>Radon</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poussières à vie longue</td>
<td>2809</td>
<td>4792</td>
<td>1375</td>
<td>8976</td>
</tr>
<tr>
<td>Contrôle équilibre radon</td>
<td>-</td>
<td>1020</td>
<td>-</td>
<td>1020</td>
</tr>
<tr>
<td><strong>Prix de revient surveillance mines (FF)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main d'œuvre et petit matériel</td>
<td>462 000,00</td>
<td>380 000,00</td>
<td>197 000,00</td>
<td>979 000,00</td>
</tr>
<tr>
<td>Location matériel et divers</td>
<td>221 000,00</td>
<td>150 000,00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Services de la mécanographie</td>
<td>1350 000,00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Uranium extrait uniquement en mine (t)</strong></td>
<td>362,7</td>
<td>267,1</td>
<td>295</td>
<td>924,8</td>
</tr>
</tbody>
</table>

Prix de revient au kilogramme d'uranium 1 350 000/924 800 = 1,45 FF/kg d'uranium
dose reçue par un travailleur exposé pendant 1 mois à 1 WL. On trouve que la dose moyenne reçue en 1972 par les mineurs du CEA est de 2,64 WLM. La norme américaine est, depuis 1971, de 4 WLM par an.

1.3.2. Cas des carrières

On a trouvé que la totalité des agents restait au niveau de 10% de la norme cumulée.

1.4. Coût de la radioprotection

Pour l'année 1972, le tableau V montre la répartition des coûts de la radioprotection pour chacune des 3 divisions minières.

L'incidence moyenne sur le coût de l'uranium est de 1,45 FF/kg d'uranium. Pour avoir le coût complet de la radioprotection, il convient de tenir compte également du coût des contrôles médicaux spécifiques, du coût de la fraction d'aération nécessité par l'évacuation du radon et des poussières, et du coût des travaux miniers supplémentaires. Ce dernier poste représente le surcoût qui est dû aux contraintes imposées par la radioprotection dans le tracé des galeries et les méthodes d'exploitation, et qui n'aurait pas existé dans le cas des mines métalliques classiques.

En actualisant les valeurs citées en [1], on obtient le tableau des coûts ci-après:

| Mesures des doses reçues | 1,45 FF/kg d'uranium |
| Contrôles médicaux spécifiques | 0,12 FF/kg d'uranium |
| Ventilation | 1,80 FF/kg d'uranium |
| Travaux miniers supplémentaires | 4,80 FF/kg d'uranium |
| Coût total: | 8,17 FF/kg d'uranium |

La conclusion est donc que pour assurer une radioprotection qui permet de maintenir les doses moyennes reçues annuellement à 23% de la norme pratique française pour le radon, ou, suivant les unités en usage aux États-Unis, à 2,64 WLM, la production doit consentir une dépense qui est de l'ordre de 10% du prix mondial de l'uranium.

DEUXIEME PARTIE

2. INCIDENCES SUR LES RESERVES

2.1. Marges disponibles au CEA

2.1.1. Norme cumulée: risque radon + risque poussières + irradiation externe

Le tableau II montre que la presque totalité du personnel «fond» est à moins de 80% de la norme cumulée et que 80% en est à moins de 50%. Une augmentation de 20% de la sévérité des normes n'entraînerait donc aucun frais supplémentaire de radioprotection.
FIG. 2. Concentrations en radon comparées aux teneurs en uranium dans les chantiers — Année 1972.
Mais il semble que le cumul ne soit pas pris en considération sur le plan international et il ne paraît pas nécessaire de traiter plus à fond cette question.

2.1.2. Norme radon: $6 \times 10^{-10} \text{Ci/l}$

La figure 1 montre qu’en 1972, la totalité du personnel «fond» est à moins de 65% de la norme pratique française et que 97% en est à moins de 50%. La valeur moyenne des doses reçues correspond à une concentration de $0,23 (6 \times 10^{-10}) \text{Ci/l}$, soit $1,4 \times 10^{-10} \text{Ci/l}$. Par conséquent, une augmentation de la sévérité de la norme pratique française d’un facteur 4 pourrait être traitée théoriquement sans frais supplémentaires par une rotation accélérée du personnel dans les différents chantiers.

2.2. Coût des améliorations possibles à court terme

2.2.1. Non ouverture des chantiers trop difficiles

S’il existait une corrélation bien établie entre le dégagement du radon et les paramètres caractéristiques du minerai et notamment sa teneur en uranium, on pourrait prévoir à l’avance quels sont les chantiers qui poseront des problèmes de radioprotection. On pourrait faire face à des normes plus sévères en renonçant à exploiter en mines les chantiers trop difficiles.

C’est pourquoi nous avons cherché à faire une exploitation statistique des données rassemblées sur la concentration en radon au cours de nos contrôles de radioprotection en vue de faire apparaître les paramètres principaux responsables de l’augmentation des concentrations [2].

Six mille résultats de 14 chantiers d’un même siège sont pris en compte. Ce travail ne fait apparaître malheureusement aucune corrélation nette. Le coefficient de corrélation entre la teneur du minerai et la concentration en radon dans les chantiers est faible, de l’ordre de 0,2 à 0,4 sauf dans un chantier à forte teneur (5,5%), où ce coefficient est plus élevé. On notera que les débits d’aérage étaient en pratique assez voisins d’un chantier à l’autre (1,4 à 2,4 $\text{m}^3/\text{s}$).

La figure 2 illustre la grande dispersion des résultats.

On doit donc renoncer à prévoir le dégagement du radon dans un chantier avant son ouverture et sa mise en exploitation.

2.2.2. Amélioration de la qualité de l’air

2.2.2.1. Amélioration de l’aérage: Il est souvent possible de réduire le risque radon en diminuant le facteur d’équilibre atteint par ses descendants, grâce à l’utilisation optimale des possibilités de la ventilation. Ceci est illustré par les figures 3 et 4 qui montrent que le facteur d’équilibre $f_{ABC}$ et donc l’énergie $\alpha$ totale ont été réduits d’un facteur 1,8 entre 1971 et 1972, simplement en éliminant des chantiers situés sur des retours d’air.

2.2.2.2. Réduction du dégagement du radon: Des travaux en cours dans notre mine expérimentale des Tenelles, illustrée par la figure 5, extrait de la référence [3] montrent que pour le même débit d’aérage, la con-
La concentration en radon et l'énergie α totale sont réduites si la mine est mise en surpression. Pour les débits d'air rencontrés en pratique, un gain de 25% environ est obtenu.

La mise en surpression de certains quartiers de mine a déjà été opérée avec bénéfice. La généralisation aux mines anciennes poserait des problèmes difficiles à l'exploitation.

**FIG. 5.** Gain obtenu en mettant la mine en surpression.
2.2.2.3. Coût/efficacité des mesures d'amélioration de la qualité de l'air:
Une estimation subjective, non basée sur une réelle analyse des postes de dépense, est que les mesures citées aux paragraphes 2.2.2.1 et 2.2.2.2 permettraient d'améliorer la qualité actuelle de la radioprotection de 25% en moyenne (la valeur moyenne des expositions radon passerait donc de 0,23 à 0,17). Le surcoût de ces mesures ne devrait pas être supérieur au coût actuel de la ventilation, 1,80 FF/kg d'uranium, soit de l'ordre de 2% du prix mondial de l'uranium.

2.2.3. Réduction du temps de travail de chaque agent

La réduction du temps de travail de chaque mineur permet une réduction proportionnelle des doses reçues, la mesure étant valable pour les trois risques contrairement aux précédentes. On notera à ce propos que toutes les mesures de réduction de l'empoussièrement étant prises dans nos mines, une réduction supplémentaire nous paraît techniquement difficile, et que l'irradiation externe est pratiquement proportionnelle à la teneur du minerai (0,5 mrem/h dans le cas d'un minerai à 1%); en ce qui concerne l'irradiation pour l'ensemble du corps, la valeur moyenne pour l'ensemble du personnel contrôlé est de 1000 mrem/an et les ouvriers de chantier dépassent souvent 2500 mrem/an.

Dans la mesure où le personnel n'est pas réaffecté à d'autres travaux et où le même salaire lui est garanti, il y a accroissement des frais de personnel. Dans ces conditions, on sait que doubler le personnel «fond» augmenterait le coût de production de l'uranium de 25%, et la valeur moyenne des expositions radon passerait de 0,23 à 0,12.

2.2.4. Abandon de l'exploitation en mine

Si à court terme, nous devions réduire la valeur moyenne des expositions au-delà de ce qui vient d'être indiqué comme possible en mine, seule l'exploitation en carrière serait acceptable. Dans ce dernier cas, les doses cumulées reçues par les ouvriers sont de l'ordre de 10% de la norme.

2.3. Améliorations possibles à long terme

Les recherches effectuées dans le laboratoire de La Crouzille et dans la mine expérimentale des Tenelles ont pour objet l'amélioration à long terme de la radioprotection. La connaissance de la manière dont les descendants du radon se répartissent sur les aérosols miniers devrait nous permettre d'en mieux contrôler les processus, en particulier en ce qui concerne la fraction des ions libres radioactifs, qui peut intervenir dans le calcul des normes radon. Simultanément, les moyens technologiques nécessaires à ce contrôle seront expérimentés.

Ceci étant, il apparaît que la tendance des exploitants est de mécaniser toujours davantage les opérations au fond. On peut montrer qu'il est possible de profiter de cette évolution pour tirer le profit maximum des recherches entreprises.

On peut, en effet, concevoir que les conducteurs d'engins seront placés dans des cabines climatisées, ce qui représente de toute façon un avantage dans les pays très chauds ou très froids, et munies de dispositifs de filtration des aérosols et de piégeage du radon, et où on pourra aussi, dans une certaine mesure, réduire l'irradiation externe.
Par ailleurs, des sections de galerie élargies seront nécessaires pour le passage et l'évolution des engins. Le coût du percement ne pourra plus être imputé même en partie à la radioprotection, et les pertes de charge des circuits d'aération diminuant, il en sera de même des coûts d'investissement et d'exploitation de la ventilation.

Enfin, le nombre d'heures de travail par tonne extraite diminuant, il y aura globalement moins de personnes irradiées.

On notera toutefois que l'augmentation des volumes abattus quotidiennement sur un chantier donné se traduira par une croissance de la concentration en radon et en poussières, et donc nécessitera une augmentation des débits d'aération.

Par conséquent, à long terme, l'exploitant pourrait peut-être, dans une certaine mesure, faire face à une augmentation supplémentaire de la sévérité des normes sans réduire le temps de travail par mineur, grâce à une radioprotection meilleure. Cependant, il serait sans doute difficile d'améliorer d'un facteur supérieur à 2 ou 3 la qualité actuelle de la radioprotection de nos mines.

La structure des coûts étant totalement modifiée dans ces perspectives à long terme, on ne peut rien dire sur ce que serait la part du coût de la radioprotection dans le prix de revient de l'uranium.

2.4. Incidences à court terme

Tout se passe actuellement comme si le prix de l'uranium sur le marché était fixé indépendamment des quantités négociées. L'incidence de l'augmentation des coûts de production sur les réserves économiquement exploitable peut se calculer à la marge en supposant le prix de vente constant, et c'est ce que nous avons fait à titre d'illustration dans le cas d'un de nos districts miniers. Si le coût de production augmente de 20%, il est nécessaire d'extraiter du minerai dont la teneur moyenne est 20% plus élevée. La figure 6 montre que la teneur de coupure, qui est de 1% dans ce district, devrait passer à 1,5%, et que les réserves en métal passeraient de 6500 t à 5700 t, soit une réduction de 12%.

Il est alors possible d'établir une loi de variation à court terme des réserves, en fonction de l'augmentation de la sévérité des normes (fig.7), loi que nous donnons surtout à titre d'illustration du raisonnement, et qu'il ne faudrait pas transposer sans précautions. On a tenu compte de ce que, au CEA, au prix actuel, 20% de l'uranium produit est extrait en carrière.

2.5. Incidences à long terme

S'il nous a été possible de prévoir à court terme l'évolution de la loi d'offre du producteur en fonction des coûts de la radioprotection, il n'en est plus de même à long terme, la structure des coûts, comme nous l'avons indiquée, risquant d'être totalement modifiée dans le cas de l'exploitation en mines. Dans le cas des carrières, les réserves et les coûts croissent, en première approximation, proportionnellement.

De même, la loi de demande d'uranium sera aussi très modifiée, en hausse vraisemblablement, par suite de l'accroissement des besoins en énergie; le prix tendra à être beaucoup plus une fonction de la quantité vendue, et même, à la limite, la quantité vendue mondialement deviendra
FIG. 6. Réserves du district A — Tonnage de minerai, métal, et teneur moyenne en fonction de la teneur de coupure (Cas d'une augmentation du coût de 20%).
FIG. 7. Variation à court terme des réserves en fonction de la norme radon (hypothèse du prix constant de l'uranium).

FIG. 8. Offre et demande à court terme et évolution à long terme.
indépendante du coût, étant fixée par le nombre de centrales nucléaires
en activité. On a représenté (fig.8) l'allure générale des lois d'offre et
de demande à court terme ainsi que leurs évolutions possibles à long
termes. L'intersection des courbes d'offre et de demande, qui indique la
quantité négociée, pourrait très bien se retrouver, à long terme, en hausse
par rapport aux quantités qui seraient actuellement négociables, ce qui
signifie que les réserves pourraient à l'heure actuelle être sous-estimées.
On conclut qu'à long terme, le coût des mesures de radioprotection
pourrait être sans influence notable sur le volume des réserves économiquement exploitées.

CONCLUSIONS

La surveillance permanente des conditions de travail dans les mines
d'uranium du CEA nous permet de faire respecter efficacement les normes
en vigueur et d'avoir également une idée réaliste des conséquences que
pourrait avoir une augmentation de la sévérité de ces normes, qui ne
devraient être modifiées qu'avec prudence.

Nous pensons que l'amélioration de la protection des travailleurs, pris
individuellement, sera obtenue beaucoup plus par l'observation stricte
des normes actuelles que par l'adoption de normes plus sévères, qui
devraient porter d'ailleurs non seulement sur la valeur moyenne mais sur
la courbe des fréquences cumulées des doses reçues.

On doit considérer que, dans la mesure où le coût d'une radioprotection
efficace représente une part importante du coût de production, chaque
société minière ne la mettra en place que si elle est assurée que ses
concurrentes sont soumises aux mêmes contraintes. A cet égard, la mise
en place d'une réglementation précisant dans le détail la manière dont
doit être effectuée la mesure des doses reçues par le personnel est
indispensable.

REFERENCES

[1] ZEGERS, J. C., PRADÉL, J., BILLARD, F., Radioprotection dans les mines d'uranium françaises,
Bulletin d'information ATEN (Association technique pour l'énergie nucléaire) n° 81 (nov. 1969).
(sept. 1971).
[3] DUPORT, Ph., MADELAINE, G.J., Influence du mode d'aérage sur le dégagement du radon dans une
mine d'uranium laboratoire, à paraître.

DISCUSSION

F. E. McGINLEY (Chairman): I should like to ask about the expression
"radon has been rejuvenated" which you use in your presentation. Would
you explain what you mean by that term?

P. ZETTWOOG: In an atmosphere which has a high concentration of
radon you have to wait for about three hours before all the radon daughters
are in equilibrium. In view of the fact that the transit time of the air which
passes through the mine is always less than 10 minutes, equilibrium is
never in fact reached and the energy of the radon daughters is therefore much lower than one would have at equilibrium. This corresponds to a 'younger radon' than if it were in equilibrium and this is why we use this expression.

F. E. McGINLEY (Chairman): I have one other question and that relates to smoking in the mines. I noticed in one of the photographs that one of the miners was smoking. Do you have no prohibition against smoking in the underground mines in France?

Y. FRANÇOIS: No, there is no prohibition against smoking in the mines in France for historical reasons. At a certain time the miners were asked not to take any alcoholic drinks down the mines and it was very difficult to put up a second prohibition by asking them not to smoke either. It is, however, highly probable that in the coming years smoking will in fact be prohibited in CEA mines.

P. ZETTWOOG: I should like to say that we have some work underway in co-operation with physicians to study toxicology, and we are trying to determine the effect of tobacco smoke on the cancer that is induced in rats. A paper will be prepared on this subject soon.

P. M. C. BARRETTO: I was interested to see that there is a very large range in the costs if you follow the 4 WLM. I note that the major problem is how the operators are to estimate these concentrations, and the pit officials when they go there to inspect. From your presentation it seemed that you have a very good control on the concentration in your mine and, if I recall correctly, almost a daily sampling from most of the works. Probably the range of prices we saw in Mr. McGinley's paper is mainly based on sedimentary type ore deposits; I think in France, however, most of the mines are in hard rock so the ventilation problems in your mines are less. Control of concentration could therefore be better with hard rock than with sedimentary rocks.

P. ZETTWOOG: What I am saying only concerns deposits in hard rock where the porosity is very small. I think that is a very favourable factor. The mines about which I have spoken provide about 90% of what is being produced in France. The remaining 10% comes from other mines operated by private enterprise, and we have absolutely no right to inspect these. Therefore I am not in a position to tell you about what is going on there.

Y. FRANÇOIS: As regards the mines in Africa with which the CEA is associated, the working regulations for these mines are more or less the same as those we have in France.

P. M. C. BARRETTO: In Brazil we have only a very small underground operation. The radiological control there is the responsibility of another department, that which is in charge of radiological control in the whole country. They come, to do the sampling, to determine the concentrations and they report if the ventilation should be improved.

However, because of the monopoly, all the costs are absorbed by the government, and therefore it is not easy to estimate the costs or the influence of radiological and safety control on the final price of the uranium. I would like to hear other participants' comment on their experience, and what can be done to give the operator a certain say on the radiation control, especially in the USA.

A. GOODWIN: In the United States of America, the basic responsibility for controlling radiation and assuring that miners do not become overexposed
rests with the mine operator. He must provide his own sampling and ventilation personnel to accomplish this goal. However, we do have a Federal inspection force and many States have their own inspection force to assure compliance with Federal and State regulations. At the present time we have about 140 inspectors on the Federal inspection staff to cover the entire USA, and they must inspect for health and safety compliance in everything from sand and gravel pits to all underground mines. Our present policy is to try to inspect each underground mine at least four times a year. We do have co-operative agreements with several States and these include the major uranium-mining States. Although we have a State plan, the Federal inspectors provide at least one inspection per year, but the State has to supplement the Federal inspections and it is their responsibility to provide at least four inspections a year in underground mines. Now many States provide more frequent inspection of small uranium mines and, as I have said earlier, at least in Colorado they provide something approaching one inspection per month, from which the mine operator can then perform exposure calculations for his employees.

F.E. McGINLEY (Chairman): Thank you Mr. Goodwin. On this same subject, Mr. Barretto might be interested in knowing that there was a study made a few years ago by the USAEC's New York Health and Safety Laboratory to characterize atmospheres in several US uranium mines and to determine the frequency of air sampling required to estimate reliably the exposure of individual workers. It is my recollection that the study showed that weekly air sampling in each working area was ample for calculating a time-weighted exposure for record-keeping purposes.

C. PALMITER: I was surprised, Mr. Zettwoog, when you gave the figures on your external whole-body irradiation per month. They ranged around 130 millirad. As I recall it, your ore percentage is lower than that in the USA and I do not believe our external measurements on a monthly basis are as high as yours. I am curious to discover the reason why you have such apparently high gamma readings?

P. ZETTWOOG: The facts and the figures on which we are basing ourselves are given in section 1.4 of my paper. They refer to the centre of a gallery which was dug in rock with a uranium percentage of 0.1%. We have 0.5 mR/h as the exposure. I do not know whether you would agree with this value; the galleries are about 2 m in diameter. Does this figure seem acceptable?

C. PALMITER: Yes, it appears reasonable, but it is still high.
EFFECTS OF RADIOLOGICAL AND WASTE-MANAGEMENT LEGISLATIVE CONTROLS ON URANIUM PRODUCTION COSTS

with specific reference to the Beaverlodge Operation of Eldorado Nuclear Limited

D.D. BELL
Eldorado Nuclear Limited,
Ottawa, Ont., Canada

Abstract

EFFECTS OF RADIOLOGICAL AND WASTE-MANAGEMENT LEGISLATIVE CONTROLS ON URANIUM PRODUCTION COSTS WITH SPECIFIC REFERENCE TO THE BEAVERLODGE OPERATION OF ELDORADO NUCLEAR LIMITED.

Within 10 years, up to 1973, the cost of reducing the radiation exposure in uranium mines from 1 working level (W.L.) to <0.3 W.L., in constant (1973) dollars, has been $1.07 per ton of ore milled. The cost of waste management has added $0.19 per ton. Factors which may vary these costs are location, geological occurrence of the ore, and imposition of regulations not foreseen at the inception of the mine. Improvements were accomplished by a major increase in volume of ventilation and a general co-operation in the application of controls. The sampling of all working areas is done by plan, and the results are announced monthly, including an underground exposure summary giving cumulative exposures since 1966. Waste management was improved by re-routing of effluents, by construction of secondary and tertiary dams to increase the retention time and afford emergency safeguards, and by chemical treatment to render certain pollutants insoluble.

The sum of these added costs may significantly affect the mine cut-off grade, and hence the published data on reserves throughout the uranium mining industry may become invalid.

INTRODUCTION

This paper is not intended to be representative of conditions throughout the uranium mining industry in Canada, but rather covers the specific situation at Eldorado Nuclear's Beaverlodge Operation. However, it should be useful as a reference for new mines which may be found in similar geographical, geological and climatic conditions as those which obtain at Beaverlodge.

Legislation regulating the uranium mining industry in Canada falls within Federal jurisdiction as enacted by the Atomic Energy Control Act and is administered by the Crown Corporation, The Atomic Energy Control Board. In those Provinces where uranium is being mined, the Control Board assigns certain safety inspection responsibilities to the Provincial Mining Authorities concerned. With respect to regulations covering waste disposal and water quality criteria at the mines, each Province has its own Standards of Criteria. Unfortunately, these are not uniform nor are they administered under one department.

---

1 Tons referred to are short tons unless otherwise specified.
**HISTORY**

Eldorado Nuclear Limited, a Crown Corporation, had the first two operating uranium mines in Canada. The Port Radium Operation commenced production for uranium in 1942, prior to which it was mined for radium recovery, and it closed down when ore reserves were exhausted in 1960. The second mine was the Beaverlodge Operation which commenced production in April 1953 and will continue to operate for many years to come.

**LOCATION**

Beaverlodge is located in the northwest corner of the Province of Saskatchewan, eight miles north of Lake Athabaska and approximately sixty miles south of the Northwest Territories. Transportation of personnel and supplies is via aircraft and originates from Edmonton, Alberta, 450 miles to the southwest. In the summer, bulk supplies are brought in by barge from Waterways, Alberta, down the Athabaska River and across Lake Athabaska and thence by truck to the mine.

The climatic conditions of the area can be quite extreme, ranging from 60°F below zero to as high as 90°F above. The average temperature of the two coldest months, January and February, is about 25°F below zero.

---

**FIG. 1. Diagram of Beaverlodge Operation.**
MINE DESCRIPTION

The mine has been developed around two main orebodies, the Fay orebody which lies in the immediate footwall of a major fault and the Verna orebody which is in the hanging wall. At present, because of its higher grade, mining is concentrated in the Fay orebody. The mineral being mined is pitchblende which occurs in secondary fracture structures associated with the major faults.

The mine has been developed through three shafts and two internal winzes and covers a strike length of over three miles. Active mine working is presently concentrated between the 17th to the 24th Levels, about 3500 feet deep, but the recently completed Fay Winze will develop areas down to 5500 feet below the surface (Fig.1). Stoping methods used are essentially horizontal cut and fill or variations thereof, together with square set recovery of sills in wide stoping areas. Deslimed mill tailing is employed exclusively for backfill (Fig.2).

MINE STATISTICS

Development Drifting ........ 346 000 feet
Raising ..................... 120 500 feet
Shafts ....................... 10 200 feet
Diamond Drilling .......... 1 600 000 feet
Tons of Waste Removed ...... 2 500 000 tons
Tons of Ore Treated ......... 8 500 000 tons
Pounds U₃O₈ Recovered ...... 33 500 000 lb

To adequately ventilate the many working areas in a mine as complex as Beaverlodge is a major undertaking. Reference is made to a paper by Smith in which costs of about 30 cents per ton mined are quoted for providing ventilation which would reduce radon concentrations to approximately one Working Level or a cumulative exposure of 12 W.L.M. for the year. This was at a time when working areas were concentrated in the upper levels of the mine.

Since that time Eldorado has reduced the levels of radon daughter concentrations to the point where the median exposure of all employees in a twelve month period totals about 2.0 Working Level Months, or a monthly exposure average of 0.2 W.L.

To accomplish these results, constant surveillance by the ventilation department, mine supervisors and the co-operation of all employees, plus substantial capital and operating funds, are required.

---

FIG. 2. Typical stope ventilation — mining westwards.
As only one half of the mine is presently being operated, the description and costs of ventilating will only pertain to half the system.

VENTILATION SYSTEM

The Fay ventilation plant has two Joy axivane fans each capable of delivering 150 000 ft³/min of air at a static pressure of 8.5 inches of water gauge. To heat the air in the winter months, a steam-to-water and water-to-glycol heat exchanger system is used. The heated glycol is then pumped through a series of coils capable of heating 300 000 ft³/min of air from -60°F to plus 30°F. This requires approximately 29 000 000 B.T.U. per hour, or 29 000 pounds of steam at 40 lbf/ft². Fortunately, the heating season is limited to the period of October to April. The plant is fully automated and alarmed.

The air from the ventilation plant is passed down through a 14ftX14ft cross-sectional raise for a length of about 4500 feet. The air is taken off every second stoping level, through controlled ventilation doors, with the alternative levels being used for exhaust passageways to the exhaust raise. The main exhaust raise, 10 ft X 10 ft in cross-section, plus the three surface shafts and smaller auxiliary openings are more than capable of handling the 300 000 ft³/min input.

Extensive auxiliary ventilation is used to circulate fresh air into drift headings and stopes not directly serviced by the main air stream. The best results have been obtained by blowing into a working place rather than exhausting from it, by using 19 inch Aerofoil electric fans blowing through lightweight plastic tubing.

VENTILATION DEPARTMENT

Currently the personnel consists of one Senior Engineer, an assistant, and one ventilation surveyor. The underground crew consists of five men, three for hanging fans and ductwork and two for building bulkheads and doors.

TYPES AND FREQUENCY OF SURVEYS

In comparison to the radon sampling frequency of three per year in 1963, the following surveys are conducted currently:

(1) A minimum of two samples for radon daughters and dust are taken in each working stope monthly. If any abnormal conditions occur the areas will be sampled more frequently until the condition is corrected.

(2) All travelways, development headings, crusher stations, backfill storage areas, etc. are sampled for radon daughters monthly.
(3) All mine openings to surface are sampled weekly, for radon and radon daughters.

(4) Volume surveys - stope areas - once monthly
    - total mine - every three months.

(5) Radon Gas Survey - stopes and drifts - every three months
    - travelways - every six months

(6) Radon Daughters and Dust Surveys in the Mill - every three months.

(7) Stope Ventilation Plans - updated monthly.

(8) Temperature and Humidity Surveys - monthly.

(9) Pressure Surveys - every six months.

(10) Long-Range Plans - as required.

Reports are issued monthly on:

(1) Manpower Working Place Calculations - showing detailed exposure calculations for the month.

(2) Underground Exposure Summary - showing cumulative figures since start of IBM records, November 1966.

(3) Underground Exposure Report - showing individual exposures for past 12 months, 6 months, 3 months.

(4) Statistical Program - showing frequency table with calculated median for current month, three, six and twelve months for the entire underground employees.

All working place radiation levels are posted monthly on the mine notice board, and underground employees are given their individual, cumulative exposure record upon request.

COSTS

The costs associated with a program of this nature based on a capital write-off of ten years and averaging the yearly ventilation raise development costs on a level per year basis (equivalent to one year's ore supply) are as follows:

<table>
<thead>
<tr>
<th>Capital</th>
<th>Total Cost</th>
<th>Yearly Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Ventilation &amp; Heating Plant</td>
<td>$350 000</td>
<td>$ 35 000</td>
</tr>
<tr>
<td>2. Vent Raise 14 ft x 14 ft at $100/ft</td>
<td>19 000</td>
<td></td>
</tr>
<tr>
<td>3. Exhaust Raise 10 ft x 10 ft at $40/ft</td>
<td>7 600</td>
<td></td>
</tr>
<tr>
<td><strong>SUBTOTAL</strong></td>
<td><strong>$ 61 600</strong></td>
<td></td>
</tr>
</tbody>
</table>
Yearly Operating Cost

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct:</td>
<td></td>
</tr>
<tr>
<td>Ventilation Crews and Supplies</td>
<td>$102,000</td>
</tr>
<tr>
<td>Power</td>
<td>$114,000</td>
</tr>
<tr>
<td>Heat</td>
<td>$45,400</td>
</tr>
<tr>
<td>Indirect:</td>
<td></td>
</tr>
<tr>
<td>Overhead &amp; Administration</td>
<td>$80,000</td>
</tr>
<tr>
<td><strong>SUBTOTAL</strong></td>
<td><strong>$341,400</strong></td>
</tr>
<tr>
<td><strong>TOTAL YEARLY COST OF CAPITAL &amp; OPERATING</strong></td>
<td><strong>$403,000</strong></td>
</tr>
<tr>
<td>Cost per ton of ore milled</td>
<td>$1.61</td>
</tr>
</tbody>
</table>

As previously mentioned, the cost of ventilating in 1963 to obtain approximately a 1 W.L. condition was $0.30 per ton, or converted to 1973 Dollars by applying a 6% escalation per year over ten years, the cost in today's dollars would be $0.54 per ton. Stated simply, the cost to improve the mine atmosphere at Eldorado from an average of 1 W.L. to less than 0.3 W.L. has amounted to ($1.61 - $0.54) $1.07 per ton of ore milled.

To relate this increased cost to the subject matter posed to this Panel is very difficult, as so many intangibles enter the picture. However, the most important criteria affecting the change in the ore reserve classification because of increased cost are the selling price of the product, the market demand for the product, the distribution of grade throughout the ore zones, the percentage utilization of plant capacity, and the corporate philosophy on return on investment, just to mention a few.

Considering only current conditions and keeping in mind that the mine is operating at half capacity and mining only the higher-grade ore zones, the loss in reserves, when pricing uranium at $7.00 per pound U₃O₈, amounts to approximately 8%. If tomorrow the selling price were to change or the grade of ore to be mined, then obviously the tons of reserves must change and could be lower or higher.

**DISPOSAL OF WASTE EFFLUENTS**

When mining first began at Beaverlodge early in 1953, disposal of tailings, mine discharge waters and effluents from the plant were restricted only to the extent that:

1. tailings could not be directly deposited into a lake which was a source of drinking water;
2. raw sewage from the plant or townsite had to be processed to meet the coliform criteria then in existence;
(3) sources of domestic water drawn from a water course into which mine or mill effluents had been discharged upstream were monitored on a voluntary basis with no specific guidelines issued.

Since the late 1960's when environmental pollution became a common household word, Federal and Provincial Authorities have been most active through research and investigations in determining today's acceptable standards for waste disposal. In the past two or three years, most provinces have enacted new air, water and waste discharge regulations.

This legislation has had a significant impact on Beaverlodge operations, not to mention every other mining project in Canada. There is, however, a marked economic difference between meeting the criteria for a mine just starting production with planned engineering to meet the new criteria, and for a mine that has been operating for twenty years. In the first case, the costs of environmental regulations are taken into account prior to the decision to commence production. In an old mine the added costs could prove prohibitive as I think has been the case for several small American uranium mines.

At Beaverlodge, work is proceeding on the means to meet the most recent Saskatchewan regulations which became effective January 1, 1970. All effluent streams are being sampled and analysed on a regular basis (minimum of four times a year) with individual samples being analysed for as many as sixty-five separate parameters. Previously, monitoring was carried out regularly, but analysis was limited to uranium content, radioactivity, pH, coliforms, B.O.D., chlorides and conductivity. As a result of the more complete analysis and further research, methods of meeting the new criteria have been partially resolved.

At present the following changes have been made in operating practice:

(1) The overflow from the water reservoir has been diverted by pipeline to the natural creek bed rather than letting it flow through the mine waste pile because of the risk of picking up radium and radon contamination.

(2) The service building sewage system, although processed through a septic tank, has been diverted by a pipeline to a sewage lagoon rather than discharged through the mine waste pile because of the risk of picking up contamination, as mentioned previously.

(3) The mine water discharge system has also been piped to a diversion pond rather than letting it percolate through the waste pile. More will be said about treatment of this water later.

(4) Slimes high in radium content from the underground sumps, formerly disposed of on the waste pile, are now pumped to a diversion pond and treated.
(5) To control the water level and thus the settling area in this diversion pond, an access road and dam had to be built with a controlled overflow point.

(6) Discharge from the hydraulic desliming backfill plant, formerly deposited into a tailings lake with an uncontrolled outlet into the natural water course, now has an outlet control dam regulating the settling period.

(7) The tailings formerly deposited are covered by water, but because of fluctuations in milled tonnage affecting the tailing discharge rate plus spring runoff, and heavy rainfall activity, the tailings overflow could at times be quite cloudy. Two additional dams and an access road downstream of the original tailings dam have been built, therefore, with the twofold purpose of increasing retention time and providing protection against failure of the primary dam or breaks in the tailings pipe-line.

(8) A chemical plant to treat the tailings discharge, together with a new power line, is to be erected at these last two dam outlet control points. The treatment will be the addition of barium chloride to precipitate the radium as barium sulphate, a highly insoluble compound.

(9) A chemical plant to treat the mine discharge water was installed in the service building and piped to the diversion pond along with the sewage.

The capital costs to initiate the first stage of the programme total $80,000. An additional $100,000 is budgeted over the next five years.

The yearly costs to maintain and operate this programme total $25,000.

Because of insufficient operating experience at this time, it is impossible to state whether increased expenditure may be required. However, based on a ten-year write-off for capital, the yearly operating cost increase for effluent treatment per ton of ore milled amounts to:

<table>
<thead>
<tr>
<th>Total</th>
<th>Yearly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital</td>
<td>$180,000</td>
</tr>
<tr>
<td>Research</td>
<td></td>
</tr>
<tr>
<td>Operating</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>$48,000</td>
</tr>
</tbody>
</table>

COST PER TON MILLED $0.19

SUMMARY

The cost of reducing radon daughter concentrations underground ...... $1.07/ton
The cost of treating effluents ...... 0.19/ton
TOTAL COST INCREASE ............... $1.26/ton
CONCLUSION

(1) All underground uranium operations will incur increased production cost as legislative restrictions become more vigorous towards lowering the permissible levels of radon and radon concentrations.

(2) All uranium mines will incur increased production costs from increasing legislative restrictions on effluent discharges.

(3) Unless there is a compensating increase in selling price for uranium, ore reserve totals as now classified will have to be reduced.

(4) Any decrease in reserves will have a significant impact on production capability of the industry to meet the forecasted increase in demand.

(5) Within practical limitation, more restrictive environmental control can be met but only at an economic disadvantage to individual operations.

ACKNOWLEDGEMENTS

The author would like to extend his thanks to Eldorado Nuclear Limited for permission to publish and to the staff of the Beaverlodge Operation for their co-operation in the preparation of this paper.

DISCUSSION

P.E. McGINLEY (Chairman): In regard to the radiation standard used in Canada, is it an environmental concentration or do you have a cumulative exposure level similar to what we have in the USA?

D.D. BELL: Newfoundland has a four working-level month per annum regulation; Ontario recently passed legislation allowing eight working-level months for 1973, reducing to six working-level months in 1974. The only other province which mines uranium is Saskatchewan, and in the Mining Act there it says that as a guideline the ICRP recommendations made in 1963 will be used, so we do not really have a national regulation as such, although we are aiming at four working-level months per annum.

P. ZETTWOOG: I should like to know whether the dollars you use in your paper are Canadian or US dollars, and I would also like to know what the market price is for uranium?

D.D. BELL: The dollars referred to are Canadian dollars. In reply to your second question, I think everybody in the room would quote a different market price. I cannot give you one. I use $7 in calculating what the loss in ore reserves would be to obtain this increase at our present production. I am not saying that that is the market value.

P. ZETTWOOG: Is that the cost price?
D.D. BELL: I was using that as a selling price in my calculation, but I do not say that that is the selling price on the market. I had to use some figure in order to calculate what the loss in reserves would be for this increased cost per ton, and I used $7.

J.A. PATTERSON: I interpreted your statement to be that you assumed these conditions at $7, and if to that were added $1.26 you would experience an 8% loss in reserves.

D.D. BELL: $1.26 per ton, added to our cost per ton of operating, makes a difference of 8% in our cut-off grade — if we then calculate our cut-off grade for what we would have to increase to to obtain the same unit cost per pound if we are to sell it at $7.

S.R. AUSTIN: You mention the use of barium chloride to precipitate the radium. That will be very effective; do you know what actual effect this has upon the release of radon from your tailings?

D.D. BELL: I am afraid we only did laboratory tests on it to see what would be required to precipitate it out, i.e. how much per ton we would have to plan on in order to have a basis for setting up our operating system, since it is quite a way from the mine. We did calculations on the size of building and equipment to be introduced into the weir system and the dams, but I cannot give you an answer to your question on radon.

G.R. YOURT: I am not certain whether I understand the question correctly, but barium chloride, as we use it in Canada, is required to reduce the concentration sufficiently for the tailings to be suitable to be discharged into the stream. It has really no relation to the radium in the tailings storage.

S.R. AUSTIN: What I was interested in was that, if you have precipitated the radium but the particle size of the radium-barium mineral precipitated is small enough, you will probably still have a large escape of radon, although you have effectively stopped the radium.

D.D. BELL: Our legislation quotes 3 picocuries of radium per litre in drinking water, and it is to fulfill this requirement that the discharge from our control points must be kept down to that level. Our settling is in open air so, from the point of view of radon release, it is very small. The precipitate is very fine and the increased radon release would just be to the air anyway. The problem you raise would not be important as the dilution would be very high.

J.A. PATTERSON: I was wondering if Mr. Bell might comment on how his cost experience might compare with that of other Canadian mines, particularly those in the Elliot Lake area.

D.D. BELL: I will ask Mr. Yourt to quote them verbally.

G.R. YOURT: I am afraid I have not got them in the form you would like them. I am looking at a paper published in the Canadian Mining Journal of October 1972, and they give an operating cost of labour and material, and a total, the latter being 24 Canadian cents for the year 1971 per ton milled. That is from the Rio Algom Mines. They do give some capital costs of excavation of raises and installation of a heating plant between 1967 and 1971, amounting to a grand total to date of Can. $1 448 000. This is not translated into cost per ton. Denison Mines increased their ventilation from 240 000 ft³/min in various stages to 650 000 ft³/min, and the capital cost in doing so was Can. $1,25 million. Incidentally, the operating costs for 1972 at Denison, that is operating, labour, material and power costs, were 30.1 cents per ton milled. Now in order to go deeper they have quite
a sizeable project in operation, the new raise costs and equipment totalling $1.4 million. In addition to this $1.4 million fresh-air raise that they are working on now (25 ft in diameter), they expect to have to add an exhaust raise costing almost $0.5 million. Their tailings capital costs since 1969 are about $1 million, while their budgeting for up to 1990 for impoundment is $6 million. Tailings operation costs 30 cents per ton. I regret that I cannot answer in any more detail than that.

J.A. PATTERSON: As I understand it, there was no tightening of standards in Ontario, so these costs would merely be associated with meeting the previously existing standards.

G.R. YOURT: The mines have, of course, been progressively reducing the concentrations since 1960, apart from any regulatory requirements. They could see the stricter control coming and I think both operators endeavoured to meet the recommended levels as soon as they could. Rio Algom, for example, is down to between 0.1 and 0.2 working levels. Denison, I think, have bettered the present requirement of eight working-level months in 1973; I think they are down to six. The reason why the Code does not specify a lower concentration than 6 WLM/a after 1974 is that there is an epidemiological study being carried on, involving about seven or eight thousand miners (over an extended period), and it will depend on what is found as to whether the permissible level will be reduced further or not. If there are unfavourable indications the permissible level will go down, of course, but the companies are keeping concentrations lower than required by the regulations.

J. CAMERON: One of the statements in your paper, which I think the IAEA will be interested in, is that in all working places the radiation levels are posted monthly and underground employees are given their individual cumulative exposure record upon request. I wonder if you would comment on what practical response this has produced, and I would also be very interested to know whether this is a general practice in other countries: Do miners actually request their exposure record, and is it intelligible to them?

D.D. BELL: When we posted the notice informing the employees that they could request such information, the union requested that they all be supplied with it in total. We objected to this and said it was a personal matter, because we had just been involved with the union's request that personal medical records should not be available to departmental heads and supervisors. So following the same mode of reasoning, we argued that it was a personal matter and it would be kept personal — the miners could come if they wished. My recollection is that, since this offer was made, some 3% to 4% have made use of it; however, the possibility has only been in effect for the last three or four months, so it is difficult to evaluate as yet.
RADON IN URANIUM MINING: EFFECT OF PROTECTIVE CONTROLS ON URANIUM RESOURCES IN SOUTH AFRICAN MINES

A.C. HAASBROEK, R.S.J. DU TOIT
Department of Mines,
Pretoria, South Africa

Abstract

RADON IN URANIUM MINING: EFFECT OF PROTECTIVE CONTROLS ON URANIUM RESOURCES IN SOUTH AFRICAN MINES.

The past and the current situation with respect to the radiation levels of working atmospheres in South African gold/uranium mines is reviewed. The effect of ventilation on the radiation levels in the uranium section of a gold mine is summarized. Legislation currently applicable to the ventilation of the underground working places of South African mines is dealt with and the effect of protective controls on uranium resources is discussed.

1. INTRODUCTION

The first systematic survey of radiation levels from radon in the South African gold/uranium mines was done during the period 1958 to 1961 [1].

A second systematic survey [2] was done during the period 1968 to 1970. The survey covered 25 mines, 17 of which produced uranium. The picture which emerged was as follows:

(a) In general, the mines with higher uranium values had higher radiation levels.
(b) The radon-daughter concentration was largely affected by the rate of ventilation as signified by the time which the air was in contact with rock surfaces, referred to as the 'age' of the air in minutes.
(c) The radon was not found in or near equilibrium with its daughters, neither were the daughters found in equilibrium with one another in spite of long periods, of up to 2 h, during which the air was in contact with underground rock surfaces.
(d) The radon-daughter concentration was mostly well below 1 working level (WL), but in high-grade areas this concentration was found to be above 1 WL (1 WL = 1.3 x 10^6 MeV = 100 pCi for each of the radon daughters RaA, RaB, RaC and RaC').

The situation with respect to radon-daughter concentration of the 17 gold mines producing uranium was as follows:

(a) The average radon-daughter concentration for all except three of the mines was below 0.3 WL.
(b) The average radon-daughter concentration for the three mines mentioned ranged between 0.5 WL and 2.4 WL.
(c) The mean radiation concentration of the mine where the highest radon-daughter level was recorded was brought down from 2.4 WL to
### TABLE I. AVERAGE RADON-DAUGHTER CONCENTRATIONS OF DIFFERENT MINES

<table>
<thead>
<tr>
<th>Class of resource</th>
<th>Grade (%)</th>
<th>Air age (min)</th>
<th>Radon-daughter concentration in WL</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Slime dams</td>
<td>0.02</td>
<td>0</td>
<td>n.d.</td>
</tr>
<tr>
<td>(b) Gold/uranium mines</td>
<td>0.03</td>
<td>53</td>
<td>0.23&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>(c) Uranium/gold mines</td>
<td>0.09</td>
<td>20</td>
<td>0.09&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>(d) Copper etc./uranium mines (open cast)</td>
<td>0.004</td>
<td>0</td>
<td>n.d.</td>
</tr>
<tr>
<td>(e) Open-cast uranium mines</td>
<td>?</td>
<td>0</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

<sup>a</sup> Average of 681 observations in 16 mines.

<sup>b</sup> Average of 39 observations in the uranium section of one mine only.

n.d. = not determined, but expected to be insignificant.

Gold/uranium = where uranium is a by-product.

Uranium/gold = where gold is a by-product.

0.9 WL by decreasing the mean 'age' of the air from 68 min to 20 min by means of increased ventilation and by getting the air to the working places via shorter air routes from the surface.

In general, a positive relationship emerged between radon-daughter concentration and uranium grade as well as the age of the ventilating air. From this it is obvious that a high-grade mine, where the air has been in contact with rock surfaces for many minutes before it gets to and through the working places, will have the highest radon-daughter concentration.

### 2. RADIATION LEVELS AND URANIUM RESOURCES

For the purpose of this paper, the South African uranium resources can conveniently be subdivided into five classes which do not have the same radiation level and are not affected to the same extent by the cost of protective controls.

Table I summarizes the average radon-daughter concentrations as determined in 1970 in mines of the different classes of resources.

### 3. EFFECT OF IMPROVED VENTILATION

Improved ventilation has a profound effect on the radon-daughter levels of a mine. To illustrate this point, the experience gained at two mines is quoted below.

#### 3.1. Mine A

The ventilation in the uranium section of mine A was improved in two steps. The improvements effected were as follows:
(a) Increase of 30% in the quantity of air circulated;
(b) Better use of the available air so as to increase its face velocity by 25% on the average.

The effect of the first step on the mean working level for radon daughters was that out of a total of 37 working places surveyed before and after the improvement, 18 (= 49%) of the places returned lower readings after the improvement by a mean factor of 2.3. Hence, there was a significant improvement, but not as much as was desired.

The effect of the second step was that out of a total of 46 places surveyed before and after the change, 16 (= 35%) of the places returned lower readings after the change by a mean factor of 3. Hence, here again, there was some improvement.

A third step was taken, the accent being on the dilution of the ventilating air with fresh air which had not traversed other working faces. Areas with high activity were concentrated on. Three areas were mainly involved for which the radon-daughter concentrations in WL before and after the improvement are given below.

**First area, Mine A**

The dilution of the ventilating air with fresh air affected seven places as follows:

<table>
<thead>
<tr>
<th>Place No.</th>
<th>Before</th>
<th>After</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.4</td>
<td>0.10</td>
<td>97</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>0.17</td>
<td>93</td>
</tr>
<tr>
<td>3</td>
<td>2.7</td>
<td>0.90</td>
<td>67</td>
</tr>
<tr>
<td>4</td>
<td>2.8</td>
<td>0.99</td>
<td>65</td>
</tr>
<tr>
<td>5</td>
<td>3.3</td>
<td>0.49</td>
<td>85</td>
</tr>
<tr>
<td>6</td>
<td>2.4</td>
<td>1.40</td>
<td>42</td>
</tr>
<tr>
<td>7</td>
<td>2.4</td>
<td>1.50</td>
<td>38</td>
</tr>
</tbody>
</table>

**Second area, Mine A**

An increase of 33 m$^3$/s in the ventilation rate, of which 14 m$^3$/s could be discharged into old areas, affected three zones as follows:

<table>
<thead>
<tr>
<th>Zone No.</th>
<th>Before</th>
<th>After</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.7</td>
<td>0.1</td>
<td>86</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>0.69</td>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>0.42</td>
<td>16</td>
</tr>
</tbody>
</table>

**Third area, Mine A**

An additional fan was installed to discharge 31 m$^3$/s of air into old areas, which allowed the freshening-up of the upper levels with intake air. In addition, worked-out areas were closed off. Twelve working places were affected as follows:
It can be seen that the dilution of the air produced dramatic improvements.

3.2. Mine B

The effect of ventilation in Mine B is given in Table II. As can be seen, an increase in ventilation of 55% gave the following results:

(a) A 17% reduction in the time which the air took from the surface to reach the underground working places;
(b) A 43% reduction in the radon-daughter working level.

The different methods followed to improve the conditions confirm the outstanding benefit to be gained by getting the maximum quantity of fresh air to a working place by the shortest route.

### TABLE II. EFFECT OF INCREASED VENTILATION ON RADON-DAUGHTER CONCENTRATION

<table>
<thead>
<tr>
<th>Location</th>
<th>Ventilation (m³/s)</th>
<th>Increase (%)</th>
<th>Air age (min)</th>
<th>Reduction (%)</th>
<th>Radon-daughter concentration (WL)</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td></td>
<td>Before</td>
<td>After</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>25</td>
<td>39</td>
<td>56</td>
<td>180</td>
<td>150</td>
<td>17</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>20</td>
<td>15</td>
<td>180</td>
<td>150</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>17</td>
<td>90</td>
<td>180</td>
<td>150</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>20</td>
<td>62</td>
<td>180</td>
<td>150</td>
<td>17</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>223</td>
<td></td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>55</td>
<td></td>
<td></td>
<td>17</td>
</tr>
</tbody>
</table>
To sum up, the results of these investigations prove that significant improvements can be effected as follows:

(a) Reducing the time taken by the air to get to and through the working places by (i) increasing the rate of ventilation, and (ii) shortening the air route from the surface to the working places;
(b) Sealing off worked-out areas to prevent seepage of radon and radon-daughter concentrations from such areas into the ventilation current.

4. LEGISLATION CURRENTLY APPLICABLE TO THE VENTILATION OF UNDERGROUND WORKING PLACES

The Mines and Works Act No.27 of 1956 and the regulations framed thereunder control all aspects concerning the safety, health and welfare of persons employed in or at mines and working places.

Regarding the ventilation of underground working places, the following regulations are provided, inter alia:

(a) The ventilating air must be free from dust, smoke or other impurity;
(b) The working places of every part of a mine where persons are required to travel or work must be properly ventilated to maintain safe and healthy environmental conditions for the workers;
(c) The ventilating air must be such that it will dilute and render harmless any inflammable or noxious gases and dust in the air;
(d) The maximum quantities of gases such as carbon dioxide, carbon monoxide, oxides of nitrogen, hydrogen sulphide, inflammable gas and dust must not exceed the limits prescribed;
(e) The velocity of the air current along the working face of any stope must average not less than 0.25 m/s over the working height; and
(f) The quantity of air supplied at the working face of every development end, such as a tunnel, drive, cross-cut, raise or winze, which is being advanced, or at the bottom of any shaft in the course of being sunk must not be less than 150 dm³/s (0.15 m³/s) for each square metre of the average cross-sectional area of the excavation.

As will be noticed from this, no radiation level has as yet been incorporated in the regulations. The improvements reported have been obtained by co-operation between the Department of Mines and the mines concerned.

5. EFFECT OF PROTECTIVE CONTROLS ON URANIUM RESOURCES

Should the maximum allowable concentration of radon and radon daughters be reduced in future to 0.3 WL, the effects on the exploitation of the resources (Table I) would vary.

Thus resource (a), which is on the surface, and resources (d) and (e), which are accessible by open-cut mining operations, would not be affected.

Resources (b) and (c), however, would be affected, and some description of them is necessary for an appreciation of the position. These resources are located in the various reefs of the Witwatersrand series and
the Dominion reef series. Where the reefs of the Witwatersrand series are mined today, the primary object in almost every instance is recovery of their gold content. Moreover, in the one instance where the reefs are exploited primarily for their uranium content, this is carried out concurrently, and within the same company, with the mining of adjacent reefs which are only gold bearing. The economics of exploiting the uranium resources of the Witwatersrand series are therefore indissolubly linked with those of gold production.

Against this background the following factors would have to be taken into account in determining the effects on the uranium resources of the Witwatersrand Basin in case of a reduction of the maximum allowable concentration of radon and radon daughters to 0.3 WL:

(a) The nature of the reefs available in each mining lease area. The relative gold and uranium values of each of these reefs are of primary importance, and where 'uranium-rich' reefs are present, the deciding factor in the economics of the venture would be whether there are gold-rich reefs present which could be mined in parallel with them.

(b) The depths of the various reefs and the virgin rock temperatures associated with them. Mining in the Witwatersrand Basin is almost everywhere at considerable depths (up to 3500 m), where the control of the working environments may necessitate the combined use of refrigeration and very high ventilation rates. The high ventilation rates play no small part in ensuring that average radon and radon-daughter concentrations of the mines are in general at such low levels. In planning the extension of mining operations to progressively greater depths, increasing reliance is being placed on refrigeration and recirculation of air. Under conditions where 'uranium-rich' reefs are mined at depth, new problems might well be created in individual ventilation sections of mines, should stricter control of radon and radon-daughter concentrations call for the supply of additional ventilating air. As indicative of what might be involved, the survey by the Chamber of Mines Research Organization [2] found a number of localized areas in the gold/uranium mines with concentrations of radon and radon daughters in excess of 0.3 WL, despite the fact that the average mine values were below this level.

(c) Working costs and the price of gold. These are probably the most important factors relevant to the issue under discussion. Both are at present subject to exceptionally rapid and unpredictable change.

Under the circumstances it would be a nearly impossible task to make an assessment of the effects of stricter controls on the class-(b) and part of the class-(c) resources (Table I). A part of the class-(c) resources is located in the Dominion reef series, which is not being mined at present, and is estimated to be economically mineable only in the event of the higher price of from $15 to $19 per pound of uranium oxide materializing. Because of the relatively shallow depth of up to 1500 m, at which this reef would be mined, the ventilation problems created by stricter controls should not be as formidable as in the deep mines. However, the general low gold content of the reefs in this series precludes the mining of gold-rich reefs in parallel with the 'uranium-rich' reefs, thus making the viability of its exploitation more dependent on the price of uranium. Any increase in costs, as a result of stricter controls, would therefore have a considerable effect on this part of the class-(c) resources.
REFERENCES


DISCUSSION

F.E. McGINLEY (Chairman): You said something about a high-uranium-grade mine and you qualified it to the extent that you were not thinking in terms of uranium mining elsewhere. What in South Africa would you consider high uranium grade?

A.C. HAASBROEK: I think that over, say, 0.5 kg U₃O₈/ton would be considered as high grade.

D.D. BELL: Have you had any records of cancer in uranium miners? Your rates are so low in comparison to ours.

A.C. HAASBROEK: No. We had only three of these mines operating at the higher grade, and the Bantu miners, who only come to the mines for a contract of nine months or a year and then go home again for 9 months or a year, are not exposed for long enough to worry us at all. The white workers who are more constantly employed by the mining companies also change frequently from these mines to other gold mines so that the cumulative exposure of individual miners did not cause any concern. At present, only in one mine, I believe, there is one miner who has been there for a number of years but to my knowledge, from the records that are kept, we certainly did not have any lung cancer cases which could be attributed to uranium mining.
SUMMARY REPORT ON SESSION 1

In the absence of radiation hazards, mines are ventilated to assure the comfort of the workers and their freedom from dust and fume hazards. The costs of controlling radiation hazards in underground uranium mines arise from the need to ventilate active working places more extensively than would be necessary to control the usual mine air pollutants. There are costs for sampling and keeping records, and in some instances there are extra medical costs in addition to the usual medical services provided. Ventilation costs are divided between capital investment for fans and heating equipment and for additional mining work to provide additional or larger air courses, and operating costs for power, fuel and maintenance.

In some cases the entire radiation protection costs are charged against radiation control, in other cases costs are determined as an incremental charge to achieve a reduction in radiation levels. When two or more commodities are recovered from an ore it becomes difficult or impossible to assess the cost due to the recovery of uranium only. In South African mines, uranium is at present principally mined as a by-product of gold mining, and uranium recovery is therefore to a large extent dependent on the economics of gold mining. In some United States mines, vanadium is recovered along with uranium.

Because of the different character of ore bodies it is difficult to compare costs of radiation control. Deposits in igneous rocks have different radon emanation properties than those found in sedimentary formations. Mining methods also vary depending on ore deposits. Table I summarizes the costs of radiation control as presented by the countries reporting.

Although the various countries have different protection standards, essentially all report exposure levels of approximately the same magnitudes, as shown in Table II.

Since radiation controls affect the mining costs, any change in permissible radiation exposures will result in a change of ore reserves assuming a fixed price for uranium. Estimates were made of the effects of reduced permissible exposure levels on uranium ore reserves. Table III contains results of these estimates for each country reporting, and Table IV gives the existing protection standards for uranium mines.

IMPACT OF A MORE RESTRICTIVE RADIATION PROTECTION STANDARD

1. Demand

There was general agreement that none of the controls now in effect or likely to be adopted would have much impact on demand. Since the final cost of delivered electricity produced by nuclear generators is so little influenced by the costs of raw materials, the demand will not be affected. Within reason, existing power-generating facilities will require uranium essentially independent of cost. Raw fuel materials costs also have such low leverage on delivered power costs that no measureable effects on the decision to use nuclear or fossil fuel in new plants are foreseen.
2. Sales

If more restrictive standards are imposed to become effective during the term of an existing contract, the profitability to the mine operators may be drastically affected. However, if reduced radiation levels are anticipated, this can be taken into account in a new contract. Since no major reduction in permissible radiation levels is foreseen, no detrimental effects on future contracts are expected.

3. Exploration

Exploration activity would probably increase in the event of a more restrictive exposure standard because, as stated above, the demand for uranium would not be reduced but the availability of supply from the present operators or mines might be reduced. The type of exploration might change, concentrating on large lower-grade deposits near the surface, mineable by open-pit methods, rather than on deep, higher-grade deposits requiring underground mining.

4. Future uranium industry

As discussed above, more stringent standards would tend to discourage underground mining and encourage surface mining.

Conventional methods of ventilating underground uranium mines are approaching practical limits in the control of radon daughters at the current exposure standards. A reduction in radiation standards would generally require either the development of dramatic new technology in ventilation, i.e. much more complex conventional ventilation systems, or adapting mining methods to provide individual miner protection either through the use of personal protective equipment or through remotely controlled ore extractive methods. Any of these approaches would be expected to entail significantly higher mining costs.
TABLE I. COSTS OF RADIATION CONTROL IN URANIUM MINES

<table>
<thead>
<tr>
<th>Country</th>
<th>Costs (Fr. per kg of U)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRANCE</td>
<td>F.Pr. 1.45/45/80/45/80</td>
<td>Direct charge monitoring and control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medical services</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ventilation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Additional mining work</td>
</tr>
<tr>
<td></td>
<td>F.Pr. 5.17/45/12/80</td>
<td>Total cost of control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(25.6 F.Pr./t of ore at 0.31% U)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CANADA</td>
<td>$1.07/ton ore milled (total)</td>
<td>(Incremental cost to reduce radiation exposure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>standard from 12 WLM to 2 WLM annual exposure)</td>
</tr>
<tr>
<td>SOUTH AFRICA</td>
<td>(Not possible to determine costs at present)</td>
<td></td>
</tr>
<tr>
<td>UNITED STATES</td>
<td>$0.24</td>
<td>Average incremental costs per pound of U₃O₈ in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>concentrate to reduce radiation exposure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>standard from 12 WLM to 4 WLM annual exposure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>estimated by Arthur D. Little, Inc., range from</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0 to $0.93. Industry-estimated average</td>
</tr>
<tr>
<td></td>
<td></td>
<td>incremental costs for reducing the standard</td>
</tr>
<tr>
<td></td>
<td></td>
<td>from 12 WLM to 4 WLM annual exposure range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>from $0 to $1.75 per lb U₃O₈ with an average</td>
</tr>
<tr>
<td></td>
<td></td>
<td>of $0.70 (on the basis of an average</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.25% U₃O₈ ore)</td>
</tr>
</tbody>
</table>

TABLE II. RADIATION EXPOSURE OF MINERS IN URANIUM MINES

<table>
<thead>
<tr>
<th>Country</th>
<th>Exposure of miners</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRANCE</td>
<td>Mean exposure of all miners:</td>
</tr>
<tr>
<td></td>
<td>2.65 WLM per year</td>
</tr>
<tr>
<td>CANADA</td>
<td>Median exposure of all miners:</td>
</tr>
<tr>
<td></td>
<td>2 WLM per year</td>
</tr>
<tr>
<td>SOUTH AFRICA</td>
<td>Exposure not reported</td>
</tr>
<tr>
<td>UNITED STATES</td>
<td>Company records indicate that</td>
</tr>
<tr>
<td></td>
<td>no miner received</td>
</tr>
<tr>
<td></td>
<td>an exposure greater than 4</td>
</tr>
<tr>
<td></td>
<td>WLM in 1972</td>
</tr>
</tbody>
</table>
### TABLE III. IMPACT OF REDUCED RADIATION EXPOSURE STANDARDS ON URANIUM ORE RESERVES

<table>
<thead>
<tr>
<th>Country</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRANCE (one mine)</td>
<td>A doubling of costs for radiation control would result in a reduction in ore reserves to 85% of presently known reserves. In the extreme, where underground mining would be impossible, ore reserves would be limited to those mineable by surface methods.</td>
</tr>
<tr>
<td>CANADA (one mine)</td>
<td>The reduction of the radiation exposure standard from 1 WL in 1963 to present operating levels (median exposure 2 WLM annually) resulted in an 8% loss of mineable reserves at $7.00/lb U₃O₅.</td>
</tr>
<tr>
<td>SOUTH AFRICA</td>
<td>Quantitative estimates are not available, but only 27% of the total uranium reserves could be affected by a reduced standard.</td>
</tr>
<tr>
<td>UNITED STATES OF AMERICA</td>
<td>Estimates on the reduction of reserves in going from 12 WLM annual exposure to 4 WLM annual exposure were made by Arthur D. Little, Inc. (ADL), and by mine operators. Based on $8 per lb U₃O₅, ADL estimated only a 2% reduction in underground reserves while mine operators estimated a reduction of the order of 10%.</td>
</tr>
</tbody>
</table>

### TABLE IV. EXISTING PROTECTION STANDARDS FOR URANIUM MINES

<table>
<thead>
<tr>
<th>Country</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRANCE</td>
<td>The standard is that the activity of radon gas per litre of air shall not exceed $6 \times 10^{-10}$ Ci/litre.</td>
</tr>
<tr>
<td>CANADA</td>
<td>Federal control by Atomic Energy Control Board; but individual standards are set by Provincial Regulatory Agency. Ontario standards are presently 8 WLM annual exposure with a reduction to 6 WLM, effective in 1974. An epidemiology study including 7000-8000 miners is under way to consider whether a reduction to 4 WLM annual exposure is indicated. Newfoundland has adopted as a standard the ICRP recommendation of $3.3 \times 10^{-10}$ Ci/litre of alpha activity. Saskatchewan complies with the same standard.</td>
</tr>
<tr>
<td>SOUTH AFRICA</td>
<td>No legislative controls exist, but good co-operation between mine operators and the Department of Mines resulted in a reduction of exposures. Efforts have been directed toward reducing exposures to less than 12 WLM per year.</td>
</tr>
<tr>
<td>UNITED STATES OF AMERICA</td>
<td>Present standards are that no miner shall receive an exposure in excess of 4 WLM per year.</td>
</tr>
</tbody>
</table>
TECHNICAL PROBLEMS
OF URANIUM MINE VENTILATION

(Session 2)
VENTILATION AND OTHER PROBLEMS IN CONTROLLING RADON DAUGHTERS IN URANIUM MINES

G.R. YOURT
Toronto, Ont., Canada

Abstract

VENTILATION AND OTHER PROBLEMS IN CONTROLLING RADON DAUGHTERS IN URANIUM MINES.

In many respects the control of alpha radioactivity in mine atmospheres can be achieved by applying the same methods used for other airborne contaminants such as dust, diesel exhausts, blasting gases and methane. This is done by suppressing, confining, diluting and removing the contaminants. Some additional and special methods and problems encountered are discussed.

1. INTRODUCTION

In uranium mines it is necessary to control airborne alpha radiation in addition to other contaminants that are usually encountered, such as dust, diesel exhausts, blasting gases and occasionally methane.

Some of the problems in the application of conventional control methods (suppressing, confining, diluting and removing contaminants) and special measures are described. Other complications are also discussed.

2. SOURCE AND NATURE OF AIRBORNE RADIOACTIVITY

The ore in uranium mines contains considerably more radium than other types of rock in the earth's crust. The radium, which is a link in the uranium family decay chain, gives off radon gas while it disintegrates. Radon is a chemically inert gas which diffuses in infinitesimally small amounts in and from the rock as and after it is formed from the decay of radium.

Of much more physiological significance is the radioactive decay from radon through a series of four particular disintegration (daughter) products. These are RaA, RaB, RaC and RaC', of which RaA and RaC' are alpha emitters, as illustrated by Holleman [1] in Fig.1.

In the uranium mines these daughter products, which are either attached to dust, smoke or fine moisture droplets or unattached, may be inhaled by the workers and then deposited on the walls of the bronchial tree and lung cells. The alpha bombardment on cells from excessive deposits over a period of years has resulted in the development of respiratory cancer. This effect is well described by Holaday et al. [2] and more recently by others (see Refs [1, 3-5]).

3. CONTROL OF RADIOACTIVITY

The level of airborne radiation in a uranium mine depends largely on the emanation rate of radon gas from the solid and fractured walls, roof and
floor, and even more on the emanation rate from the broken ore resting on the floor. Recent research on the nature and rate of this emanation in ores with various porosities has been described by Schroeder and Evans [6] and by Thompkins and Cheng [7, 8]. The procedures for the measurement and prediction of emanation which they describe assist mining engineers to design the best methods and the quantities of ventilation required to control radiation.

3.1. Suppressing emanation

A considerable amount of research conducted on the feasibility of depressing the emanation of radon gas from exposed rock surfaces by means of pressurizing the mine atmosphere has been described by Schroeder et al. [9]. They found that this method is only feasible if the rock is porous and if a sink is provided to absorb the permeating gas and air. Because of the difficulty and cost of providing such sinks and the lack of permeability in most uranium orebodies the pressurizing method has not yet found appreciable application.

<table>
<thead>
<tr>
<th>ISOTOPE</th>
<th>HALF-LIFE</th>
<th>PRINCIPAL RADIATION</th>
<th>ENERGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rn-222</td>
<td>3.825 d</td>
<td>ALPHA</td>
<td>5.5 MeV</td>
</tr>
<tr>
<td>Po-218</td>
<td>3.05 min</td>
<td>ALPHA</td>
<td>5.99 MeV</td>
</tr>
<tr>
<td>Pb-214</td>
<td>26.8 min</td>
<td>BETA, GAMMA</td>
<td></td>
</tr>
<tr>
<td>Bi-214</td>
<td>19.7 min</td>
<td>BETA, GAMMA</td>
<td></td>
</tr>
<tr>
<td>Po-214</td>
<td>164 µs</td>
<td>ALPHA</td>
<td>7.68 MeV</td>
</tr>
</tbody>
</table>

FIG.1. Decay scheme for radon-222.
A variety of coatings have been tested to seal the pores and crevices of exposed rock surfaces in an effort to retard radon emanation, but none are known to be in general use. Retarding radon emanation would result in disintegration to stable lead within the rock and consequently reduce the hazard. The disintegration rate of radioactive materials such as radium cannot be altered, therefore the formation of radon gas and subsequent alpha emitters cannot be suppressed. Consequently, efforts must be concentrated on confining, diluting and removing them from the breathing areas of mining personnel.

3.2. Confining radioactivity

The most effective method for confining radon and radon daughters is to isolate mined-out stoping areas and other similar unused openings, such as headings and raises, by means of ventilation stoppings. Radon continues to emanate from solid and broken rock surfaces, disintegrates to equilibrium with the daughters and can build up to very high concentrations of radioactivity. Unless such areas are kept under vacuum by exhaust ventilation, this radioactivity will diffuse into and contaminate airways, travel-ways and active working places.

This feature creates a major problem which is not encountered in mines where airborne contaminants are produced and dispersed only by the operations. The construction and maintenance of bulkheads, which are often damaged by blasting, and the ventilating facilities for confining radiation constitute a major additional cost in mining uranium.

Mined-out working areas in non-uranium mines are sometimes used as fresh airways because of the advantage of low resistance and the tempering of air during the winter months. This has quite an economic impact when one considers that the heating capacity for one Canadian uranium mine is close to 50 million Btu/h and heating costs are nearly $100,000/a [10].

As radon is partially soluble in water and emanates from seepage, the sealing of such seepages by grouting etc. and/or by diverting the water through pipes is another effective method of confining radiation. This is another cost component not encountered in other mines.

3.3. Diluting and removing radiation with ventilation

General and auxiliary ventilation are used in uranium mines to dilute and remove radon and its daughters as well as other airborne contaminants. The methods are for the most part conventional but certain aspects will be emphasized. Details are well described by Rock and Walker [11].

3.4. General ventilation

Briefly, in the case of general ventilation, the air is introduced into the mine through one or more main fresh airways, circulated through the active working places, including travel-ways, haulage-ways, and stoping areas, and then returned to the surface through one or more return airways.

There are several types of general ventilation systems. In the blowing system, the main fan is installed at the top of the fresh airway on the surface or at the bottom of a shaft used as an airway. In an exhaust system, the fan is installed at the top of one or more return airways on the surface or at the bottom of a shaft used as a return airway.
An ideal system preferred by the author and some other ventilation engineers, especially for uranium mines, consists of a push-pull arrangement. Fresh air is delivered to the active stoping areas by means of a blowing fan through a fresh airway located centrally on the strike near or in the orebody. Contaminated air is removed through mined-out stopes and two (or more) return airways at or near the remote ends of the ore zone or sections thereof by means of exhaust fans, preferably located on the surface. The fresh-air fan handles more air than the exhaust fans so that there is sufficient to keep the travel-ways and haulage-ways ventilated and the main shaft at a slight overpressure at the collar.

The main advantages of the system described for uranium mines are as follows:

(a) Fresh air can be delivered directly to the stoping area on one or more levels enabling one-pass ventilation, if necessary.
(b) Mined-out working areas can be kept under a slight vacuum to prevent contamination of active working places.
(c) Fresh air can be made readily available for stope preparation and lateral development work.
(d) Pressures across doors and regulators in the ore zone are low.
(e) Smoke and gases from diesel haulage units will not reach the stopes where the majority of miners usually work.

If the fresh airway is located in the orebody, the air velocities should be kept sufficiently high to prevent a build-up of radiation. If footwall haulage-ways are available, they should be used for lateral distribution of fresh air.

If the ore is porous or if there is significant seepage of water carrying radon it is probably not feasible to pass fresh air through the orebody because of contamination. In such instances the fresh airway must be driven in the footwall or hangwall.

In mines where the top of the orebody is over, day, 1000 ft below the surface it may be necessary for economic reasons to use one or more shafts for transporting air in and/or out of the mine. In such instances, the main fans must be located underground because it has not been found feasible to make the headframes of operating shafts airtight. All appurtenances in downcast shafts should be fire-proof.

3.5. Air distribution

In long orebodies, experience has indicated that it is advisable to space out the airways at sufficiently close intervals along the strike (about 1500 ft) to enable good air distribution. The ability to convert a return airway to a fresh airway or vice versa adds to the flexibility and effectiveness of the system.

In uranium mines it is especially important to deliver fresh air directly to the miners and then remove air containing radon and daughters as quickly as possible. This keeps the air young in radioactivity and minimizes the growth and accumulation of radon daughter products, especially through RaB and RaC to RaC', which is the second potentially significant alpha emitter.

The importance of this age-of-air concept and methods for calculating and predicting ventilation requirements are well described in earlier publications [6-8].
In large open stopes it is very difficult and expensive to effect frequent air changes and keep the air young, especially if the air must be heated in freezing weather. Unless required for ground support, the use of backfill for reducing the size of mine openings constitutes an additional cost, but this may be justified for radiation control. If classified tailings are used as backfill, additional ventilation is required to dilute and remove the emanation of radon from the residual radium. This is true even if most of the radium is associated with the discarded slimes. If shrinkage stoping is used for mining large orebodies, additional ventilation is also required and the working areas must be kept under positive pressure to minimize the emanation of radon by seepage of air through broken ore. Studies on this problem have been described by Malygin [12].

Unless relatively high air velocities and volumes are maintained in and between working places the air becomes too contaminated to be used more than once, which is often done in non-uranium mines. At one Canadian uranium mine, fresh air is distributed and used air is collected on alternate levels.

3.6. Leakage, short circuiting and recirculation

Leakage and short circuiting of fresh air through doors, bulkheads and box holes is a problem in most or all mines. During the past three years, one uranium mining company in Canada has spent a great deal of effort and money on research to establish a continuous monitoring system of airflows. The objective is to increase the efficiency of ventilating facilities from about 55 to 80% by prompt detection, communication and corrective action when lapses in the designed airflows are registered by the continuous monitors strategically placed in distributing airways. Early work on this project has been described by Lord and Pullen [13].

Inadvertent recirculation of used air can be tolerated in some metal mines but in uranium mines it results in unacceptable build-up of radioactivity.

3.7. Pillar recovery

It is difficult to provide clean air to workers during the recovery of pillars in any open stope mining. However, some of the dust will diffuse into the open spaces, and fans can be used to disperse it. In uranium operations, the continuing emanation of radon from pillars and remnants of broken ore on the floors contaminates the atmosphere in such areas. In such instances it may be necessary to protect the workers with auxiliary ventilation.

3.8. Auxiliary ventilation

For uranium mines, all development headings and raises in ore, and also some in waste where water seepages emanate radon, and all dead-end stopes must be ventilated by means of auxiliary fans and pipe and/or flexible tubing. The blowing system provides the best protection from radiation exposure to men working at the face, provided that the fan intake is in fresh air and the end of the pipe or tubing is maintained near the workers. Semi-rigid plastic
pipe has been found to be durable for this purpose. Sufficient air must be circulated to dilute and sweep away airborne radiation at the face and in the travel-way. A complicating problem arises if there are significant emanations in a travel-way that cannot be sealed or isolated. It may be necessary to remove them by a separate exhaust system with inlets at the emanation points. The exhausted air should be delivered to a return air circuit.

3.9. Cleaning air for recirculation

Small filters are used at a number of uranium mines to remove radon daughter products from contaminated air. This air is suitable for ventilating individual working places, provided that it is delivered to such areas within a few minutes after filtration. The practice is particularly applicable in remote working places where contamination of airways is a problem.

The choice of filtering media should be made after making a study of conditions such as concentration of airborne radioactivity, dust, diesel smoke and moisture particles (or humidity). For example, following the research briefly reported by Frame [14] and subsequently described by Washington and Kruzich [15], a uranium mining company purchased a 40 000 ft$^3$/min filter fitted with heavy napped terylene bags. Based on experience with a test unit, this cloth removes less radioactivity than some other types of fabric, some with a precoating, but will present fewer operational problems, for example, resistance due to clogging by diesel smoke, dust and moisture and also excessive maintenance.

With further improvements in the technology of filter media, difficulties in meeting permissible concentrations of radioactivity and dust and the increasing capital and operating costs of mine ventilation, the practice of cleaning mine air to permit recirculation probably will increase. This may be necessary in deep mines.

There are certain limitations to the usefulness of filtration. Repeated cleaning of the same air could result in a very high concentration of radon gas because no economic method of removing it has been found. This quickly reduces the permissible period of time between filtration and use of the air. Also a question has been raised as to the relative harmfulness of the radon daughters passing through the filter compared with those that have been removed.

3.10. Respirators

Improvements in the efficiency of various types of respirators are well described in the literature. This means of protection from exposure to radon daughters in uranium mines has not received wide acceptance for strenuous work. High-efficiency conventional and battery-powered respirators have been found useful at bacterial leaching operations in mined-out areas which are difficult to ventilate. There is a need for further improvement in the comfort and convenience of this type of protection.

A very light cellulose type of disposable filter with low resistance has been found to be efficient in the removal of airborne radioactivity. Some question has been raised about the durability and actual effectiveness of the filter when it is worn during active work and repeatedly removed and replaced during a shift.
4. ADDITIONAL PROBLEMS

4.1. Monitoring instruments

The methods used in uranium mines for measuring radon daughter products for over one and a half decades were provided by Holaday et al. [2] and have been very useful. However, despite the commendable efforts of various researchers during this period, the industry is still in need of two types of instruments. One should provide the ventilation engineer an on-the-spot reading of alpha emission for control purposes; the other should provide a time-weighted exposure of the miners.

The three uranium mining companies in Canada had very discouraging experience with costly Instant Working Level Meters supplied by GeoCon, Gloucester, Mass. They are naturally hesitant to purchase other new instruments unless their reliability and usefulness is proven.

The present status of instrumentation has been well described by Breslin [16]. This information should be a useful guide in future efforts for developing better instruments. Research in this area needs to be coordinated, augmented and expedited.

In the meantime, some improvement in accuracy has been made in existing meters. Uranium mining companies in Canada are using scintillation meters with built-in scalers; the instrument technician at Eldorado Nuclear Limited additionally incorporated a very useful digital read-out into one instrument. Probably meters at other mines will be similarly converted.

4.2. Attached versus unattached radon daughters

The change in the standards adopted in the United States from 12 to 4 WLM per year resulted partly from epidemiological studies, recently reported by Lundin et al. [4], but also related to the 30 pCi/litre obtained from a formula in the 1959 ICRP Recommendations (Ref. [17], p. 23):

"Recent studies have indicated that when radon and its daughters are present in ordinary air the free ions of RaA atoms that would be present at equilibrium and these unattached atoms deliver all but a small fraction of the dose to the bronchi. Based on these measured dose rates the (MPC) a for exposure to radon and daughter products is found to be $3 \times 10^{-6}/(1+1000f)$ where f is the fraction of the equilibrium amount of RaA ions which are unattached to nuclei."

At that time it was assumed that $f$ was equal to 0.1 (10% unattached). Since then, researchers have found that about 5% or less of the radon daughters are unattached. Applying 0.05 to the formula would result in an MPC of 59 instead of 30 pCi/litre.

A clear interpretation of this formula has not been provided to the industry. If this is due to the uncertain physiological effect of attached versus unattached radon daughters it would appear that research into this aspect should be expedited. This point is raised because it probably has a significant bearing on future instrumentation for measuring and assessing exposure.
5. CONCLUSIONS

(a) Uranium mines require more ventilating and heating capacity and special control measures in comparison with other metal mines. Meeting newly adopted standards makes this even more difficult and expensive.

(b) It is considerably more difficult to design ventilation for a uranium mine than for other mines because of the inability to accurately predict the extent of emanations that will be encountered. Published results of research will be helpful but further studies are needed.

(c) There is a great need for research and improvements in instrumentation for on-the-spot measurement of concentrations to enable prompt corrective action and for assessment of cumulative exposure. This also requires research into the intricate nature of deposition and effects of attached and unattached alpha emitters.

REFERENCES

F.E. McGINLEY (Chairman): I should like to start off the discussion by asking a general question; have you noticed any constant relationship between the grade of ore mined and the radon emanation in Canadian mines? In other words, if, for example, the grade of ore doubled, would you expect to have to provide twice the amount of air to accomplish the same reduction in working levels?

G.R. YOURT: I think the most I would be prepared to say is that there is a general relationship — I do not think I would venture to say that doubling the grade would double the emanation. It would probably be very close to that, but there may be other factors that may influence this, emanations from water, for example. I think our experience is limited. In the Elliot Lake area there is not that much variation in grade.

S.R. AUSTIN: I think that there is a relationship; if you double the grade you may nearly double the emanation, though if you have ten times the grade, you do not get ten times the amount of radon produced.

Y. FRANÇOIS: You have spoken about instruments for individual protection; I suppose you mean that they cannot be carried under working conditions, that is they can only be used in exceptional cases. I am thinking of equipment such as masks, respirators, etc.

G.R. YOURT: In regard to the use of respirators, we have had a fair amount of experience with these and found it just was not practicable to expect the miners to wear the respirators while they were doing heavy work. For example, the heavy work on one particular operation was pipe fitting, and where there was any strenuous work we just could not expect the workers to wear respirators. It formed a minor part of their actual exposure in hours, and we just assumed that they did not wear respirators during those operations. A large part of the time involved in these leaching operations is spent in holding a hose to spray the walls and floor, to encourage the bacteria to get the uranium out and to digest the sulphides. During this part of the operation, miners could wear respirators. We used battery-driven types for the most part, as we found that these were better accepted. Two types were used, the one you are quite familiar with and that was developed in France, and another type developed in the USA. One has a face piece, containing the filter, a battery and a little fan driven by a battery motor, and the other has the fan and filter on the miner's belt, with a hose to the face piece. I would hope that we could get one that could be driven off the conventional cap-lamp battery without carrying an extra one, but perhaps that is too much to expect.

F.E. McGINLEY (Chairman): Has there, to your knowledge, been any work done in Canada on electrostatic precipitation to remove radon daughters?

G.R. YOURT: When I was still with Rio Algom, we purchased a small 'precipitron' unit. We had some operating problems with it, and there was insufficient encouragement to go into it extensively.

J. CAMERON: Is there any possibility that the exhaust of radon at the surface could produce any potential hazard on the surface or in surface buildings near the exhaust fan?

G.R. YOURT: Yes. If you had a fresh-air fan too close to the return airway, recirculation would be a real possibility. In fact, I recall that this did happen on one occasion with the wind blowing in a certain direction, that is towards a fresh airway.
I would just like to add a point regarding the design of ventilation systems. There is a strong tendency to use shafts as airways, to the extent of making them larger to enable them to handle more air. I think the design engineers and the people designing shafts should look at the economic aspects of designing the operating shaft only for mine operation, and use separate airways for ventilation. They should take into consideration the extra cost of making larger shafts, say concrete-lined ones, as against making the operating shaft just large enough to do the hoisting, etc., and locating ventilation ways some distance away. I am not convinced that using a production shaft or service shaft, which usually involves cross-cuts to an ore body, is the best way of providing a ventilation system, unless the ore body is very deep. We should look at the economics in that light. For a comparatively shallow ore body, for example as at Elliot Lake, the raises to the New Quirke mine are 800 or 900 feet deep and the shaft is not used for ventilation. The shaft in that case was kept neutral or slightly upcast, so that the air from the haulage ways, where the diesels operate, goes up the shaft rather than to the workings.

Although there were some strong arguments from some of the operating people in favour of using the shaft as a downcast airway, we were able to agree to use separate airways; and I believe that now they are very thankful that the airways are separate.

D.D. BELL: In Canadian operations, where you are dealing with cold weather, there is a tendency to design your plant around your shaft so that it is an integral part of the building, maintenance and everything else; this does create problems when it comes to return airways. If we had to repeat some of our designs we would change our thinking in that respect.

G.R. YOURT: I meant to say that I, too, am not in favour of using an operating shaft as an exhaust airway—I prefer to keep the shaft neutral, with leakage of fresh air from the cross-cuts and the shaft slightly upcast.
LA VENTILATION DANS LES MINES D'URANIUM

Y. FRANÇOIS, J. PRADEL, P. ZETTWOOG, M. DUMAS
CEA, Centre d'études nucléaires
de Fontenay-aux-Roses,
Département de protection,
Fontenay-aux-Roses,
France

Abstract—Résumé

VENTILATION OF URANIUM MINES.

In the first part of the paper the authors describe the ventilation of French mines in terms of the primary ventilation system, which brings the outside air close to the working places using the overall structure of the mine to form the airways, and the secondary ventilation system, which is for the distribution of the primary air or for the ventilation of the development drifts and blind tunnels. Brief mention is made of the French regulations on the ventilation of mines in general and uranium mines in particular. The authors describe the equipment used and discuss the installed capacities and air flow per man and per working place. The difficulties encountered in properly ventilating various types of working places are mentioned, such as sub-level development drifts, reinforced stopes, and storage chambers with an artificial crown.

The second part of the paper is devoted to computer calculations of the primary ventilation system. It is explained why the Commissariat à l'énergie atomique has found it necessary to make these calculations. Without restating the mathematical theories underlying the methods employed, the authors demonstrate how simple measuring instruments and a small-size computer can be used to solve the ventilation problems arising in French mines. Emphasis is given to the layout of the ventilation system and to air flow and negative pressure measurements at the base of the mine. The authors show how calculations can be applied to new heading operations, a change in resistance, the replacement or addition of a ventilator, and a new air inlet or outlet.

The authors come to the conclusion that since ventilation is at present the most reliable way of avoiding the pollution of mines, a thorough knowledge of the capabilities in this respect can often help improve working conditions. Despite the progress made, however, constant surveillance of the ventilation systems in uranium mines by a separate team with no responsibility for production problems is still necessary if high efficiency is to be maintained.

LA VENTILATION DANS LES MINES D'URANIUM.

Dans une première partie, les auteurs décrivent l'aérage des mines françaises, tant en ce qui concerne l'aérage primaire, qui amène l'air du jour à proximité des chantiers, en utilisant comme gaine l'ossature de la mine, qu'en ce qui concerne l'aérage secondaire qui assure la répartition de l'air primaire ou la ventilation des galeries en traçage et des culs de sac. Ils rappellent brièvement la réglementation française concernant l'aérage des mines en général et des mines d'uranium en particulier. Ils décrivent le matériel utilisé et indiquent les puissances installées ainsi que les débits d'air par homme et par chantier. Ils soulignent les difficultés rencontrées pour l'aérage correct de différents types de chantiers: traçages de sous-niveaux; chambre charpentée remblayée; chambre magasin sur couronne artificielle.

La deuxième partie est consacrée aux calculs par ordinateur des réseaux d'aérage primaire. Les auteurs exploitent pourquoi le Commissariat à l'énergie atomique a été amené à faire ces calculs. Sans reprendre les théories mathématiques des méthodes utilisées, ils démontrent comment, avec un outillage de mesure simple et un ordinateur de petite capacité, on arrive à résoudre les problèmes d'aérage posés par les mines en question. Ils insistent sur l'exécution du schéma d'aérage et sur les mesures de débit et de dépression au fond de la mine. Ensuite, les possibilités de calcul pour un nouveau percement, un changement de résistance, un changement ou une adjonction de ventilateur, une nouvelle entrée ou sortie d'air, etc., sont examinées.

Les auteurs concluent que l'aérage étant actuellement le moyen le plus sûr pour dépolluer les mines en question, une bonne connaissance des possibilités offertes permet souvent d'améliorer les conditions de travail. Cependant, malgré les progrès réalisés, la surveillance permanente de l'aérage des mines d'uranium par une équipe dégagée des problèmes de production, reste nécessaire pour assurer une bonne efficacité.
INTRODUCTION

Le Commissariat à l'énergie atomique (CEA) est le principal producteur français d'uranium, puisque, en 1972, sur une production métropolitaine de 1420 t, sa part est de 1320 t.

Les mines du CEA sont regroupées en trois divisions: la division de La Crouzille, la division de Vendée, la division du Forez.

Les minerais exploités ont des teneurs relativement basses, allant de un à quelques kilogrammes de métal à la tonne.

La ventilation, ou, pour employer le terme plus communément utilisé en France, «l'aérage» des travaux souterrains constitue un problème important.

Dans les mines d'uranium, en plus des gaz nocifs (fumées de tir, gaz d'échappement des locotracteurs diesel), il faut également diluer et évacuer le radon, élément de la chaîne de l'uranium à l'état gazeux.

Le but de cet exposé est de montrer les moyens employés dans les mines d'uranium françaises pour résoudre les problèmes posés par l'aérage.

Dans une première partie, après avoir rappelé la réglementation française, l'aérage des mines du CEA est décrit, tant en ce qui concerne l'aérage primaire, qui amène l'air du jour à proximité des chantiers, en parcourant les ouvrages formant l'ossature de la mine, qu'en ce qui concerne l'aérage secondaire qui assure la répartition de l'air primaire ou la ventilation des galeries en traçage et des culs de sac.

Le matériel utilisé est présenté; les puissances installées ainsi que les débits d'air par homme et par chantier sont indiqués.

Ensuite sont exposées les difficultés rencontrées pour l'aérage correct de différents types de chantiers: traçages de sous-niveaux; chambre magasin; chambres remblayées.

La deuxième partie est consacrée aux calculs par ordinateur des réseaux d'aérage primaire. On y explique pourquoi le Commissariat à l'énergie atomique a été amené à faire ces calculs.

Sans reprendre les théories mathématiques des méthodes utilisées on démontre comment, avec un outillage de mesure simple et un ordinateur de petite capacité, on arrive à résoudre les problèmes d'aérage posés par les mines du CEA.

PREMIÈRE PARTIE

AÉRAGE DES MINES D'URANIUM FRANÇAISES

1.1. RÉGLEMENTATION

Les mines d'uranium françaises sont soumises:

a) au «Règlement général sur l'exploitation des mines autres que les mines de combustibles minéraux solides» (annexe I)

Ce règlement prévoit que tous les ouvrages souterrains accessibles aux ouvriers doivent être parcourus par un courant d'air régulier, capable d'en
assainir l'atmosphère, spécialement à l'égard des gaz nuisibles et des fumées, et d'y éviter toute élévation exagérée de la température. L'air introduit dans la mine doit être exempt de gaz, vapeurs ou poussières nocifs ou inflammables.

Le débit global d'air de la mine doit être d'au moins 50 l'air par seconde et par homme présent au poste le plus chargé.

b) À la «Réglementation particulière aux mines d'uranium» (annexe II)

Cette réglementation impose, en particulier, que tous les ouvrages souterrains accessibles aux ouvriers doivent être parcourus par un courant d'air, aussi intense que possible, capable d'en assainir l'atmosphère à l'égard du radon et des poussières radioactives.

Le débit d'air de 50 l par seconde et par homme, prévu au règlement général, est très insuffisant pour maintenir la concentration en radon de l'atmosphère de nos mines au-dessous des limites admissibles.

Pour mieux situer le problème, il convient de rappeler quelques notions concernant la formation du radon et de ses produits de filiation.

1.2. DÉGAGEMENT DU RADON

Comme dans toutes les mines, les travaux d'exploitation ont pour résultat de mettre en suspension sous forme de poussières une partie des minerais. Mais, dans les mines d'uranium, une autre source de contamination atmosphérique provient de l'existence, dans la chaîne de l'uranium, du radon, gaz rare de période 3,8 jours (fig.1).

Ce gaz, formé au sein de la roche, a deux comportements possibles: ou bien il reste lié à la roche, ou bien il diffuse dans l'air du sol à travers les fissures des roches. Le gaz lié peut être libéré lorsque la roche est brisée, en particulier au moment de l'abattage. Le gaz qui se trouve dans les fissures peut diffuser jusque dans les galeries (ce deuxième comportement explique que l'on rencontre parfois des quantités importantes de radon lors du creusement de galeries absolument stériles). Il peut aussi être entraîné par les eaux dans lesquelles il se dissout; à 20°C et en régime d'équilibre, la concentration du radon dans l'eau est égale à 0,23 fois la concentration dans l'air [1]. C'est ce qui permet d'expliquer que lorsque les eaux souterraines arrivent à l'air libre (par exemple dans une galerie de mine), elles dégagent leur radon dissous, la concentration dans l'eau étant beaucoup trop élevée par rapport à la concentration dans l'air.

Une fois passé dans l'atmosphère de la mine, le radon se désintègre en donnant des atomes de corps solides: RaA (période: 3 min), RaB (période: 27 min), RaC (période: 20 min), RaC' (période: $1.5 \times 10^{-4}$ s); le radium D, par suite de sa très longue période (22 ans), ne peut atteindre qu'une concentration négligeable. On peut approximativement assimiler l'ensemble des descendants du radon à un seul corps de période 30 à 40 min. Ces particules de dépôt actif se déplacent et sont captées en très grande partie par les poussières ou aérosmols de l'air.

L'ensemble de ces particules: atomes à l'état libre, ou atomes fixés en suspension dans l'air, constitue un aérosmol radioactif qui est formé en permanence dans les chantiers miniers.
En fonction de l'âge de l'air, et par rapport à l'activité de la source de radon, les activités des produits de filiation sont les suivantes:

<table>
<thead>
<tr>
<th>Âge</th>
<th>RaA</th>
<th>RaB</th>
<th>RaC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 min</td>
<td>0,20</td>
<td>0,0027</td>
<td>0</td>
</tr>
<tr>
<td>3 min</td>
<td>0,49</td>
<td>0,02</td>
<td>0</td>
</tr>
<tr>
<td>10 min</td>
<td>0,897</td>
<td>0,14</td>
<td>0,016</td>
</tr>
<tr>
<td>30 min</td>
<td>0,999</td>
<td>0,48</td>
<td>0,18</td>
</tr>
<tr>
<td>60 min</td>
<td>1</td>
<td>0,76</td>
<td>0,5</td>
</tr>
<tr>
<td>120 min</td>
<td>1</td>
<td>0,95</td>
<td>0,86</td>
</tr>
<tr>
<td>180 min</td>
<td>1</td>
<td>0,994</td>
<td>0,97</td>
</tr>
</tbody>
</table>

On doit cependant noter qu'il est très difficile d'évaluer l'âge du radon présent dans l'air car la formation du dépôt actif peut commencer dans les fissures des roches ou dans les zones non ventilées (en particulier, anciens travaux).

Il faut un temps assez long, de l'ordre de 3 heures, pour que le dépôt actif (RaA, RaB, RaC, RaC'), soit en équilibre avec le radon.

Un des rôles les plus importants de la ventilation dans les mines d'uranium est de chasser le radon de la mine le plus rapidement possible pour limiter au maximum la formation de dépôt actif.
1.3. AÉRAGE PRIMAIRE

a) Définition: On appelle circuit d'aérage primaire un ensemble: puits, galeries, plans inclinés, montages, formant l'ossature de la mine, utilisé pour amener l'air du jour à proximité des chantiers et évacuer l'air pollué.

La circulation d'air dans ce circuit est toujours assurée par un ou plusieurs ventilateurs électriques. Les puits creusés dans le stérile, sont utilisés comme «entrée d'air».

b) Types d'aérage: Aérage en boucle, aérage diagonal, mine en pression, mine en dépression.

- Aérage en boucle (fig. 2)

Si les puits d'entrée d'air et les puits de retour d'air sont côte à côte, on a un aérage en boucle. Ce système peut amener des courts circuits entre les puits et, d'autre part, l'air franchit deux fois la distance des puits au quartier, ce qui augmente la résistance de la mine.

Ce système n'est pas employé dans les mines du CEA.
- Aérage diagonal (fig. 3)

Les puits d'entrée d'air et de sortie sont éloignés l'un de l'autre. Les circuits sont plus courts et moins résistants. C'est cette méthode qui est appliquée dans les mines d'uranium françaises.

- Mine en dépression ou en surpression

En principe, dans les chantiers, l'aérage est ascendant pour favoriser la tendance naturelle de l'air qui monte en se réchauffant.

Généralement les mines du CEA sont mises en dépression par un ou plusieurs ventilateurs placés au jour (fig. 4).

Lorsqu'il s'agit de mines exploitées depuis plusieurs années, les zones de vieux travaux communiquent souvent avec la surface par des orifices difficiles à contrôler en permanence (éboulement). La mise en dépression de la mine provoque des pertes d'air par court circuit.

Dans la mine 1, en 1967, le court circuit par les vieux travaux était de 5,5 m³/s, soit 21% du débit total du ventilateur assurant l'aérage du quartier de mine.

---

**FIG. 4.** Mine en dépression.
Dans des cas semblables, la solution adoptée dans les mines françaises consiste à installer les ventilateurs au fond de la mine de façon que la partie de la mine en activité soit en dépression et que la zone de vieux travaux soit en surpression (fig. 5).

Duport et Madelaine [2] ont montré que, à ventilation égale, la concentration du radon dans l'air d'une mine est plus faible si la mine est en surpression que si la mine est en dépression. Les concentrations dans l'air sont réduites d'un facteur 0,5 à 0,9 suivant le débit d'aération.

La mise en surpression de l'ensemble des mines anciennes poserait des problèmes difficiles à résoudre; cependant, l'application de ce système à certains quartiers de mine a toujours été bénéfique.

On peut citer le cas d'une mine de la Division B. Dans cette mine, la moyenne des concentrations en radon était montée à $3.3 \times 10^{-10}$ Ci/l en 1965, lorsque la mine était en dépression. La mine a été mise en surpression (la puissance installée étant inférieure à celle utilisée précédemment) et la moyenne des concentrations en radon est redescendue à:
soit un facteur de réduction d'environ 0,8.

c) Matériels utilisés: Les ventilateurs d'aérage primaires employés sont tous du type hélicoïdes.

La gamme des puissances est la suivante: 18, 50, 64, 160 chevaux (ch). Excepté pour le 64 ch, le calage de l'angle des pales est variable, ce qui permet d'obtenir les débits et dépressions souhaités.

La figure 6 indique les débits et dépressions que l'on peut obtenir avec ces ventilateurs:
- les débits: de 10 à 55 m³/s;
- les dépressions: de 30 à 250 mm d'eau.
**AERAGE PRIMAIRE**

Décembre 1972

<table>
<thead>
<tr>
<th>LOCALITÉ</th>
<th>Type Ventilateurs</th>
<th>Quantité</th>
<th>Débits, m$^3$s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VENDEE</td>
<td>Ventilateurs</td>
<td>3</td>
<td>87</td>
</tr>
<tr>
<td>ECARPIERE</td>
<td>de 64 ch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMMANDERIE</td>
<td>de 64 ch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CROUZILLE</td>
<td>de 50 ch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FANAY</td>
<td>Ventilateurs</td>
<td>5</td>
<td>111</td>
</tr>
<tr>
<td></td>
<td>de 18 ch</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>de 4 ch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MARGNAC</td>
<td>Ventilateurs</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>de 18 ch</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>de 10 ch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FOREZ</td>
<td>Ventilateurs</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>de 4 ch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOIS NOIRS</td>
<td>Ventilateurs</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>de 160 ch</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>de 64 ch</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**AERAGE SECONDAIRE**

Dans le chantier (2 hommes) de 1,5 à 2,5 m$^3$s$^{-1}$

FIG. 7. Aérage ( primaire et secondaire) dans les trois divisions de mines du CEA.

Installés en relais au fond, ou bien pour l’aérage de chantiers particuliers et de petits quartiers, on utilise des ventilateurs de 4 ch, 10 ch, 18 ch, permettant d’obtenir des débits de 6 à 22 m$^3$/s, avec des dépressions de 10 à 55 mm d’eau.

Les portes sont utilisées pour l’établissement de circuits complexes d’aérage primaire. Leur mise en place est destinée, soit à empêcher le passage de l’air (portes pleines) sans arrêter la circulation du personnel et des convois, soit simplement à freiner le courant d’air (portes à guichet).

On place en général deux portes successives pour former un sas et éviter les perturbations dans le circuit d’air au moment de l’ouverture de l’une des deux.

Les barrages sont mis en place pour isoler les parties de la mine déjà exploitées, des zones de travail. Ces ouvrages sont le plus souvent réalisés par des murs de parpaings de 15 ou 20 cm d’épaisseur, recouverts d’un enduit en ciment.

Il est habituellement nécessaire de prévoir, à la base des barrages, le passage de l’eau en provenance des vieux travaux. L’étanchéité au passage de l’eau doit être réalisée au moyen de siphons.

**d) Débits:** La figure 7 et le tableau 1, indiquent les puissances installées, les débits d’air, ainsi que les concentrations en radon dans les galeries formant l’ossature des mines.
<table>
<thead>
<tr>
<th>Tableau I. Abraçage primaire dans les mines du CEA (année 1972)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sages miniers</td>
</tr>
<tr>
<td>Mine 1</td>
</tr>
<tr>
<td>Mine 2</td>
</tr>
<tr>
<td>Mine 3</td>
</tr>
<tr>
<td>Mine 4</td>
</tr>
<tr>
<td>Mine 5</td>
</tr>
<tr>
<td>Mine 6</td>
</tr>
</tbody>
</table>
Le débit de «50 l'air par seconde et par homme présent au poste le plus chargé» prévu par le règlement général est insuffisant pour «assainir l'atmosphère à l'égard du radon et des poussières radioactives».

Dans les mines d'uranium françaises, les débits d'air primaires sont au moins 30 fois plus élevés que ce minimum réglementaire. Cela représente la mise en action de moyens considérables sans équivalent avec les mines métalliques courantes et même avec les charbonnages où cependant les problèmes d'aérage sont très importants. C'est ainsi qu'en moyenne le poids d'air remonté du fond, dans les mines d'uranium françaises, représentait en 1972, de 17 à 27 fois le tonnage de minerai extrait.

1.4. AÉRAGE SECONDAIRE

a) Définition: On appelle aérage secondaire l'aérage des chantiers ou des galeries en cul de sac que le courant d'air primaire ne parcourt pas.

b) Type d'aérage: Le mode de ventilation secondaire employé dans les mines du CEA est, en général, la ventilation soufflante. Quelques essais de ventilation aspirante ont été effectués, mais ils n'ont pas donné de résultats satisfaisants.

La distance limite des canalisations rigides d'aérage au front de taille est de l'ordre de 10 à 15 m pour éviter leur détérioration par les tirs.

Dans le cas de l'aérage aspirant, l'air frais est aspiré directement dans la canalisation et dépollue mal la partie de la galerie comprise entre le front et l'extrémité de la gaine rigide.

Dans le cas de l'aérage soufflant, on prolonge la canalisation rigide par une gaine souple et la dépollution de la zone de travail peut se faire de façon satisfaisante.

Pour le creusement de longues galeries, on utilise le plus souvent une méthode mixte (fig. 8).

Un ventilateur aspirant d'une puissance relativement élevée assure une entrée d'air dans la galerie et aspire l'air pollué qu'il rejette dans une gaine soufflante dans un retour d'air.

Un ventilateur de plus faible puissance, placé en amont aérage, pulse l'air et assure la dépollution de la zone de travail.

Ces deux ventilateurs sont déplacés lorsque l'avancement des travaux le nécessite.

Ce système a l'avantage de maintenir une atmosphère saine dans la galerie de roulage.

Les chantiers d'abattage sont le plus souvent parcourus par le courant d'air primaire. Cependant, la zone de travail se trouve fréquemment hors de ce circuit.

Pour obtenir une bonne dépollution, on utilise également une ou plusieurs colonnes d'aérage secondaire (fig. 9).

L'aérage secondaire représente un effort important.

Par exemple, en 1972, sur la division B, il y avait:

Mine 1: 17 ventilateurs de 8 ch et 3 ventilateurs de 22 ch alimentant 3 150 m de canalisations d'aérage secondaire, la longueur moyenne des installations étant de 160 m.

Mine 2: 9 ventilateurs de 8 ch, pour 950 m de canalisations d'aérage.
FRANÇOIS et al.

Ventilateur aspirant (22 en)

Entrée d'air

Ventilateur soufflant (8 ch)

FIG. 8. Aérage pendant le creusement d'une galerie avec un ventilateur aspirant et un ventilateur soufflant.

air pollué

porte

chantier

ventilateur

I < 10 m

air frais

FIG. 9. Coupe verticale d'un chantier.
c) Matériel utilisé: Les ventilateurs employés sont tous du type héli-coïdes avec redresseur.

Pour l’aération soufflant les puissances utilisées sont de 5 et 8 ch pouvant assurer des débits de 2 à 3,8 m$^3$/s (fig. 10).

Pour l’aération mixte, on prend un ventilateur de 22 ch pour l’aspiration.

Les débits vont de 4 à 6 m$^3$/s.

Les canalisations d’aération secondaire sont, soit:

- **Rigides (métalliques ou plastiques)**
  - Les raccordements sont assurés par des manchettes en caoutchouc.
  - Les diamètres vont de 300 à 600 mm, celui utilisé le plus souvent étant de 500 mm.

- **Souples (polyéthylène)**
  - L’épaisseur de la gaine varie suivant l’utilisation de 200 à 500 μm.
  - Les diamètres vont de 300 à 900 mm, ordinairement, on utilise ceux de 500 ou 600 mm.

   d) Débits: Les débits indiqués au paragraphe c) (Matériel utilisé), sont des débits théoriques. Le débit réel des ventilateurs secondaires dépend beaucoup de l’installation de la colonne d’aération (longueur, qualité de l’installation, etc.).

Les débits mesurés dans les chantiers vont de 1,5 à 2,5 m$^3$/s pour dépouiller une zone où travaillent ordinairement deux ouvriers.
1.5. CONTROLE DE L’AÉRAGE

Le but à atteindre est d’assurer au personnel une atmosphère convenable par la dilution suffisante et l’évacuation rapide des fumées de tir et du radon. Les contrôles portent naturellement sur la quantité d’air (mesure des débits) et sur la qualité (mesure des concentrations en radon).

Le Service technique d’études de protection et de pollution atmosphérique (Steppa), chargé du contrôle radiologique des divisions minières a été amené tout naturellement à prendre en charge les mesures d’aé rage. En effet, la quantité et la qualité de l’air envoyé dans les chantiers est un des paramètres les plus importants qui conditionnent les concentrations en radon.

Le système français pour contrôler la concentration du radon dans l’air, impose un nombre très important de prélèvements (36 700 en 1972, pour un effectif contrôlé de 621 mineurs). Ceci nécessite la présence permanente d’agents du Steppa au fond des mines. Ces agents, en plus de leurs prélèvements de gaz et de poussières, mesurent également les débits d’air.

— Aé rage primaire

Des mesures de débits d’air sont effectuées chaque mois en de nombreux points de la mine afin de constater les changements qui auraient pu éventuellement se produire dans les circuits primaires.

Le bon état des ouvrages est vérifié et les anomalies immédiatement signalées.

Les agents du Steppa participent également aux études d’aé rage qui seront décrites dans la deuxième partie de cet exposé.

— Aé rage secondaire

Chaque semaine, les débits d’air sont mesurés dans les chantiers.

La qualité de l’installation est vérifiée, en particulier, le préleveur s’assure que le débit d’air primaire est suffisant pour alimenter le ventilateur secondaire.

Lorsque l’installation est défectueuse, la modification est:

a) Signalée et exécutée dans les plus brefs délais, s’il s’agit de gaine souple à remplacer;

b) Signalée à l’ingénieur de la mine (par exemple, dans le cas de déplacement de ventilateur secondaire) qui prend ses dispositions pour faire exécuter la modification rapidement.

On voit l’importance de la présence permanente des agents de contrôle. Cette présence permet de limiter à quelques jours au maximum la dégradation des conditions de travail.

On peut citer un exemple récent (juin 1973) de cette efficacité:

Dans un chantier, la teneur du minerai était de l’ordre de un pour cent. L’agent du Steppa signale un aé rage secondaire mal installé: la gaine plastique était en mauvais état et éloignée du point de travail. La moyenne des concentrations en radon, relevée au cours de la semaine, était alors de \(6,9 \times 10^{10}\) Ci/l. La semaine suivante, après remise en état de la colonne d’aé rage secondaire, la concentration en radon n’était plus que de \(3,0 \times 10^{10}\) Ci/l.
1.6. METHODE D'EXPLOITATION ET AERAGE

- Travaux préparatoires

Au début des travaux préparatoires, l'aérage est assuré au moyen d'un ou plusieurs ventilateurs placés au jour et soufflant dans des canalisations rigides ou souples (fig. 11); le retour d'air s'effectue par le puits. Dès que les galeries ont atteint une longueur suffisante, on creuse une série d'ouvrages verticaux (montages), pour relier les différents étages et percer au jour (fig. 12).

L'obligation d'amener un air exempt de radon à proximité des chantiers conduit à adapter ou modifier de façon sensible les techniques habituelles de reconnaissance; en particulier l'accès direct aux zones minéralisées est à proscrire et l'on trace une galerie appelée «parallèle» qui servira à la circulation de l'air, au passage du personnel et à l'évacuation des produits (fig. 13). C'est le plus souvent dans ces galeries parallèles que seront placés les ventilateurs secondaires chargés d'aérer les chantiers.

- Travaux d'exploitation

Lorsque les travaux préparatoires sont terminés dans un quartier, on procède aux travaux d'abattage pour lesquels plusieurs méthodes ont été ou sont employées; dépilages par sous-niveaux et chambres vides, dépilages par chambres magasin (sur stot, sur couronne artificielle), dépilages par chambres remblayées (remblayage simple, remblayage hydraulique).
Puits

FRANÇOIS et al.

Ventilateur primaire

DD—
C D—

Pc Ventilateurs secondaires 0 Barrage
Canalisation d'aérage • p- Air frais
Porte avec réglage » Air pollué

FIG. 12. Travaux préparatoires.

Ventilateurs secondaires
Canalisation d'aérage
Porte avec réglage
Barrage
Air frais
Air pollué

FIG. 13. Galerie appelée «parallèle».
Les problèmes d’aérage sont assez différents suivant la méthode employée:
Dans le cas des sous-niveaux et chambres vides (fig. 14), on se trouve en présence d’un vaste quadrillage de galeries et de montages dans lesquels les déperditions d’air peuvent être importantes.
Les barrages nécessaires à l’établissement d’un circuit d’aérage correct sont en général des ouvrages légers en raison de leur courte durée.
et les fuites d'air y sont nombreuses. Il est très difficile d'utiliser le circuit d'air primaire dans ces travaux et le nombre de ventilateurs secondaires est souvent élevé.

Au moment du tir, les produits abattus peuvent obstruer l'extrémité des sous-niveaux et l'air ne passe plus dans la chambre, jusqu'au moment où une quantité suffisante de minerai a été enlevée.

Le retour des ouvriers après tir nécessite un aérage par canalisation souple et la concentration du radon dans l'air est souvent très élevée.

Après abattage des produits, les épontes minéralisées dégagent du radon qui vient polluer le circuit d'aérage primaire de la mine.

Cette méthode n'est pratiquement plus employée dans les mines du CEA.

Dans le cas des chambres magasin, on a le plus souvent la possibilité de faire passer l'aérage primaire par le front de taille (fig. 15).

Dans cette méthode d'exploitation, on enlève uniquement le volume dû au foisonnement, de façon à prendre pied sur le minerai abattu pour forcer les mines en couronne. Le minerai repose, soit sur un stot de protection, soit sur une couronne artificielle constituée de fers IPN sur lesquels sont posés des planches, le tout reposant sur des fers UPN boulonnées aux épontes. Dans les deux cas on laisse, de place en place, des orifices pour le chargement des produits dans les galeries de base (trémières de chargement).

Le volume du minerai stocké devient ainsi très vite important et les quantités de radon libérées augmentent dans la même proportion.

FIG. 15. Exploitation par chambres magasin.
La quantité d'air frais nécessaire à une dilution convenable du radon peut ainsi être de l'ordre de 8 à 10 m³/s pour un front de 30 à 50 m de long, avec du minerai courant (1 à 3%, par exemple).

Comme dans le cas des sous-niveaux et des chambres vides, lorsque la chambre est vidée de ses produits, les épontes minéralisées dégagent du radon qui vient polluer le circuit d'aération primaire de la mine.

Cette méthode d'exploitation est aujourd'hui abandonnée.

Dans le cas des chambres remblayées, on adopte autant que possible le même mode d'aération que précédemment, mais dans ce cas, le gros inconvénient dû à la masse du minerai abattu disparaît. Si les remblais sont constitués par du stérile «tout venant», on constate des déperditions d'air importantes au travers de ces remblais. Ces fuites d'air à travers d'anciens dépilages viennent polluer l'air sain dans la mine.

Par contre, cet inconvénient est totalement évité dans le cas du remblayage hydraulique (fig.16, 17).

En effet, les remblais sont suffisamment tassés pour être imperméables à l'air.

Ces remblais sont constitués par des sables qui sont les stériles en provenance des usines de traitement chimique du minerai et dont la granulométrie varie de 40 à 500 μm. Les éléments de moins de 40 μm ont été
préalablement séparés par cyclonage et rejetés, car ce sont eux qui contiennent la plus grande partie du radium. Il serait, en effet, anormal de renvoyer dans la mine des produits radifères qui augmenteraient d'autant les concentrations en radon. Les essais effectués en laboratoire ont montré que la fraction dont la granulométrie est inférieure à 40 µm dégage 10 à 15 fois plus de radon que les produits plus gros.

C'est cette méthode qui est actuellement employée dans les mines d'uranium du CEA.

1.7. VENUES D'EAU ET AÉRAGE

Dans le chapitre 1.2. (Dégagement du radon), nous avons vu que les eaux souterraines dégagent leur radon dissout lorsqu'elles arrivent à l'air libre. Parfois les quantités de radon libérées sont suffisamment importantes pour polluer les circuits d'aération.

La canalisation de ces eaux pose souvent des problèmes difficiles à résoudre et l'on préfère cimenter les orifices des venues d'eau. C'est la solution qui a été adoptée en 1969 pour la mine n° 3.
A la suite d'une campagne de sondages, on constate de fortes venues d'eau chargées en radium (1000 à 7000 pCi/l), et en radon. La décision est prise de reboucher les 12 trous de sondage les plus polluants avec du ciment injecté sous pression.

L'obturation des trous de sondage a eu un double effet:
- 1) de diminuer de 50% la concentration en radium dans les eaux d'exhaure de la mine;
- 2) de diminuer de 40% la concentration en radon dans l'air des galeries.

DEUXIÈME PARTIE

CALCULS PAR ORDINATEUR DES RÉSEAUX D'AÉRAGE PRIMAIRE

Si la ventilation des premiers petits chantiers de recherche ou des exploitations minières à leur début ne pose guère de problèmes, il en est tout autrement des sièges miniers actuels où la complexité des circuits d'aérage nécessite pour leur résolution l'emploi de méthodes mathématiques complexes.

La quantité d'air qui parcourt les travaux est en général bien connue puisque les débits sont mesurés fréquemment; par contre, on semble oublier souvent les caractéristiques fondamentales des circuits d'aérage: résistance des ouvrages, dépression, travail utile des ventilateurs.

Cette ignorance conduit à de graves mécomptes, car le plus souvent, lorsqu'on se contente de remplacer un ventilateur par un autre plus puissant, sans étudier le circuit d'aérage, l'augmentation de la puissance installée est sans commune mesure avec le gain de débit obtenu.

Une autre raison a obligé les mines d'uranium françaises à rechercher l'optimisation de ces circuits d'aérage: depuis plusieurs années déjà, les teneurs moyennes des minerais extraits sont en augmentation constante. Il fallait donc rechercher constamment le meilleur aérage possible pour maintenir les concentrations de radon à un niveau acceptable.

Les figures 18, 19 et 20 montrent l'évolution des teneurs des minerais et, parallèlement, l'évolution des concentrations dans les chantiers et les galeries.

L'installation d'ordinateurs au centre mécanographique de Limoges a permis, depuis 1966, d'adapter à nos problèmes d'aérage, une méthode de calcul qui utilise la théorie des réseaux maillés [3-5].

2.1. DEFINITIONS

Un nœud, ou jonction, est constitué par la réunion de deux ou plusieurs ouvrages miniers en un même point.

Une branche est un élément de galerie, puits, montage, etc. joignant des nœuds.

Une maille est un ensemble de branches parcourues en circuit fermé.

Un réseau maillé est un ensemble de mailles.
FRANÇOIS et al.

DANS LES CHANTIERS
DANS LES GALERIES
TENEURS MOYENNES U

FIG. 18. Evolution des concentrations en radon (Division A).

DANS LES CHANTIERS
DANS LES GALERIES
TENEURS MOYENNES U

FIG. 19. Evolution des concentrations en radon (Division B).
2.2. UNITES ET FORMULES

a) Perte de charge

Soit un élément de circuit AB (fig. 21) (puits, galeries, montage, etc.), lorsque l'air circule de A vers B, on constate qu'il y a perte de charge, c'est-à-dire, dégradation de l'énergie.

Cette perte de charge s'exprime en mm d'eau, elle est de la forme:

\[ H = R Q^2 \]  \hspace{1cm} (1)

- \( H \) = en mm d'eau
- \( R \) = en kilomurgue
- \( Q \) = en m\(^3\)/s

FIG. 20. Evolution des concentrations en radon (Division C).

FIG. 21. Sens du courant d'air dans un élément de circuit.
b) Résistance

Si dans la formule (1), $H = 1 \text{ mm d'eau}$, $Q = 1 \text{ m}^3/\text{s}$, on a:

$$R = 1 \text{ kilomurgue}$$

Le kilomurgue est la résistance d'un ouvrage qui laisse passer $1 \text{ m}^3/\text{s}$ sous une dépression de $1 \text{ mm d'eau}$.

L'ordre de grandeur des résistances des principaux ouvrages miniers français est:

- Puits de $3,60 \times 2,20$: $5$ à $8$ murgues par étage de $40 \text{ m}$
- Puits de $6,00 \times 3,20$: $1$ à $1,5$ murgue par étage de $40 \text{ m}$
- Galeries de section $4$ à $5 \text{ m}^2$: $15$ à $50$ murgues pour $100 \text{ m}$
- Galeries de section $6$ à $7 \text{ m}^2$: $8$ à $15$ murgues pour $100 \text{ m}$
- Montages section $2$ à $2,5 \text{ m}^2$: $90$ à $100$ murgues pour $40 \text{ m}$
- Montages section $3$ à $4 \text{ m}^2$: $30$ à $40$ murgues pour $40 \text{ m}$
- Plan incliné de section $5$ à $6 \text{ m}^2$: $4$ à $6$ murgues par étage de $40 \text{ m}$ de relevée.

c) Orifice équivalent

L'orifice équivalent d'une mine parcourue par un débit total $Q$ est la section en $\text{m}^2$ d'une ouverture en mince paroi qui laisse passer, sous une dépression $H$ identique à celle de la mine, ce même débit $Q$:

$$a = 0,38 \frac{Q}{\sqrt{H}}$$

$a = \text{en m}^2$
$Q = \text{en m}^3/\text{s}$
$H = \text{en mm d'eau}$

La plupart des mines d'uranium françaises avaient des orifices compris entre $0,8$ et $1,2 \text{ m}^2$, les changements de circuit ont considérablement amélioré ces orifices qui sont actuellement compris entre $1,5$ et $2 \text{ m}^2$.

d) Puissance nécessaire à la ventilation

Cette puissance est donnée par la formule:

$$P_{ch} = \frac{Q \times H}{75}$$

$P = \text{en ch}$
$Q = \text{en m}^3/\text{s}$
$H = \text{en mm d'eau}$

ou en remplaçant $H$ par sa valeur tirée de (1):

$$P_{ch} = \frac{R Q^3}{75}$$

A résistance égale, la puissance varie comme le cube du débit.
FIG. 22. Schéma d’aérage d’une mine.
2.3. SCHEMA D'AERAGE

Lors de l'étude d'un circuit d'aérage, le premier travail qui s'impose est la représentation des ouvrages de la mine à étudier sous forme d'un schéma traduisant le plus fidèlement possible, tout en la simplifiant, l'ossature de la mine.

Ce travail ne peut être exécuté que par un agent connaissant parfaitement les ouvrages anciens et actuels et leurs diverses intercommunications.

Le schéma (fig. 22) est la représentation en réseaux maillés d'une mine.

2.4. MESURES AU FOND DE LA MINE

Une fois le schéma d'aérage établi, il faut connaître avec la meilleure précision possible la résistance de chaque branche. Pour cela, on mesure $Q$ et $H$ et on en déduit facilement $R$.

$$R = \frac{H}{Q^2}$$

a) Débit

On choisit, si possible, dans la galerie une partie rectiligne et à section constante. On détermine la surface des sections de galeries par la méthode des photoprofils.

---

**FIG. 23.** Photoprofil réalisé au 1/50 avec appareil polaroid type 220. Eclairage lampe phare 30 W, section 5,30 m².
FIG. 24. Anémomètre Paul Gothe 0,5 à 20 m/s.

FIG. 25. Anémomètre électronique sensible à photo diode marque Sepema, licence Cherchar.
La section à mesurer est matérialisée par un trait de peinture blanche, la photographie est exécutée à l'aide d'un appareil polaroid qui fournit une photo de format 9 x 12 (fig. 23).
L'éclairage est fourni par un phare portatif de 30 W.
La planimétrie est effectuée au jour par les services topographiques.
On mesure la vitesse du courant d'air à l'aide d'un anémomètre (fig. 24, 25).

b) Dépression

Pour mesurer la dépression, on utilise un manomètre Béri droit pour la lecture entre 20 et 130 mm (fig. 26), incliné pour la lecture entre 0 et 20 mm (fig. 27).
La méthode employée est la suivante: on déroule un tuyau en vinyl, stocké sur touret, tout le long de l'ouvrage dont on veut connaître la perte de charge; on place à une extrémité l'appareil de lecture et à l'autre extrémité la prise de dépression statique (fig. 28).

Pour la mesure de dépression au ventilateur, on procède de la même façon, en se plaçant à 5 ou 6 m en amont et en aval du ventilateur.

2.5. PRESENTATION DES MESURES

Ces mesures sont reportées:

1) sur un tableau indiquant en face de chaque branche les résultats obtenus, tant pour les débits que pour les dépressions;
2) sur le schéma d'aérage, pour vérifier si les lois des réseaux maillés, analogues aux lois de Kirchhoff en électricité, sont respectées:

- **Lois des nœuds**: La somme algébrique des débits aboutissant à un nœud est nulle.
- **Lois des mailles**: La somme algébrique des pertes de charge des branches composant une maille parcourue toujours dans le même sens est nulle.

2.6. **CALCULS SUR ORDINATEURS**

Le responsable des mesures adresse au Centre mécanographique de Limoges:

- le schéma du réseau à étudier;
- la récapitulation des mesures.


2.7. **RÉSOLUTION DES PROBLÈMES**

Lorsqu'on dispose d'un réseau de départ équilibré, on peut étudier par simple changement des données de base, les nouveaux débits et pertes de charge obtenus dans chaque branche par:

- la mise en place d'un nouveau ventilateur
- la mise en place d'un ou plusieurs ventilateurs de relais
- l'ouverture ou la fermeture de portes ou barrages
- la diminution de la résistance des ouvrages de retour d'air
- la création de nouveaux ouvrages
- la combinaison de ces possibilités.

On peut également déterminer:

- le ventilateur primaire le plus économique pour un débit général donné
- l'emplacement le plus judicieux d'un ventilateur
- l'opportunité de nouveaux creusements.

L'application la plus intéressante de la théorie des réseaux maillés est le calcul, par la méthode des débits imposés, des ventilateurs et freins nécessaires à l'établissement d'un régime d'aérage donné.

2.8. **RÉSULTATS OBTENUS**

Malgré les progrès réalisés, l'étude détaillée d'un réseau d'aérage demande encore beaucoup de travail. Il faut, en effet, effectuer avec le plus grand soin les mesures au fond et conduire les calculs avec méthode, si l'on veut être assuré d'un résultat appréciable.

Les améliorations spectaculaires obtenues sur les divisions minières justifient ces efforts.

On peut prendre par exemple le cas de la mine n° 5 (tableau II).
TABLEAU II. AMÉLIORATIONS OBTENUES DANS LE RÉSEAU D'ÀÉRAGE DE LA MINE N° 5

<table>
<thead>
<tr>
<th></th>
<th>1966</th>
<th>1972</th>
</tr>
</thead>
<tbody>
<tr>
<td>Puissance installée</td>
<td>100 ch</td>
<td>94 ch</td>
</tr>
<tr>
<td>Débit àérage primaire</td>
<td>70 m³/s</td>
<td>100 m³/s</td>
</tr>
<tr>
<td>Concentrations en radon</td>
<td>3,3·10⁻¹⁴ Cl/l</td>
<td>2,3·10⁻¹⁶ Cl/l</td>
</tr>
<tr>
<td>dans les chantiers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentrations en radon</td>
<td>2,5·10⁻¹⁰ Cl/l</td>
<td>1,4·10⁻¹⁰ Cl/l</td>
</tr>
<tr>
<td>dans les galeries</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ces résultats sont encourageants puisque:
- La puissance nécessaire pour obtenir 1 m³/s d'air primaire est diminuée d'un facteur 0,65, ce qui permet d'augmenter le débit général de la mine.
- La protection du personnel est améliorée, puisque les concentrations en radon dans les chantiers et les galeries ont diminué.

Pour être encore plus complet, il faut ajouter que la teneur des minerais extraits a augmenté, entre 1966 et 1972, d'un facteur 2,7.

CONCLUSION

Actuellement, le moyen le plus efficace pour dépolluer les mines d'uranium est une excellente ventilation.

L'étude des circuits d'àérage a permis d'améliorer la qualité de l'air circulant dans les galeries, mais cette amélioration serait illusoire sans la surveillance permanente de l'àérage des chantiers par une équipe dégagée des problèmes de production.

La bonne collaboration qui s'est établie entre les services d'exploitation et les services de contrôle a permis (malgré des teneurs de minerais plus élevées), dans tous les cas une observation stricte des normes et souvent une amélioration des conditions de travail.

REFERENCES

[6] LE POLLES, C., DUMAS, M., Calcul des réseaux maillés d'àérage sur ordinateur, publication interne CEA.
ANNEXE I

EXTRAITS DU RÈGLEMENT GÉNÉRAL SUR L'EXPLOITATION DES MINES AUTRES QUE LES MINES DE COMBUSTIBLES MINERAUX SOLIDES ET LES MINES D'HYDROCARBURES EXPLOITÉES PAR SONDAGE

TITRE VII: Aérage

Chapitre I: Courant d'air

Art. 146. — Tous les ouvrages souterrains accessibles aux ouvriers doivent être parcourus par un courant d'air régulier, capable d'en assainir l'atmosphère, spécialement à l'égard des gaz nuisibles et des fumées, et d'y éviter toute élévation exagérée de la température. L'air introduit dans la mine doit être exempt de gaz, vapeurs ou poussières nocifs ou inflammables.

Art. 147. — Les voies et travaux insuffisamment aérés doivent être rendus inaccessibles aux ouvriers. Le retour dans ces ouvrages ne doit avoir lieu que sous la direction d'un surveillant.

Art. 148. — Le débit global d'air de la mine doit être d'au moins cinquante litres d'air par seconde et par homme présent au poste le plus chargé.

Art. 149. — L'assainissement de l'atmosphère des ouvrages doit y éviter tant le manque d'oxygène que la présence de gaz toxiques en quantité dangereuse; est considérée en particulier comme dangereuse une teneur, même locale, en oxyde de carbone égale ou supérieure à cinq pour dix mille (5/10 000).

Art. 150. — Sauf exception motivée, la vitesse du courant d'air au lieu de travail doit être telle que les températures au thermomètre sec et au thermomètre mouillé soient en rapport avec le travail à fournir.

Art. 151. — Les foyers d'aérage sont interdits.

Art. 152. — Sauf dans la période préparatoire, l'aérage par goyots est interdit.

Art. 153. — § 1. — Un courant d'air établi ne doit être obstrué ni par du matériel ni par une accumulation de produits ou de matériaux.

§ 2. — Les puits, galeries et autres voies qu'emprunte le courant d'air doivent être maintenus en bon état d'entretien et demeurer facilement accessibles dans toutes leurs parties, même à des sauveteurs munis d'appareils respiratoires.

§ 3. — Les ventilateurs principaux installés au fond ne doivent pas empêcher le personnel de gagner les issues imposées par l'article 57.

Art. 154. — Tout ventilateur principal installé au jour ou au fond doit être muni d'un appareil à lecture directe indiquant les dépressions ou surpressions, ainsi que d'un dispositif avertisseur des arrêts intempestifs.
Chapitre II: Répartition de l'air

Art. 155. — Dans les galeries très fréquentées, dans les galeries établissant une communication entre voies principales d'entrée et de retour d'air, ainsi qu'en tout point où l'ouverture d'une porte risquerait de provoquer une perturbation notable dans l'aérage, on ne doit employer que des portes d'aérage multiples, convenablement espacées; des mesures doivent être prises pour que l'une au moins de ces portes soit toujours fermée.

Art. 156. — §1. - Toute porte d'aérage doit se refermer d'elle-même.
 §2. - Sauf pour le passage d'un convoi, il est interdit de caler dans la position d'ouverture une porte d'aérage en service.
 §3. - Toute personne qui a ouvert une porte d'aérage doit s'assurer qu'elle se referme d'elle-même dès qu'elle cesse d'être maintenue volontairement ouverte, faute de quoi elle doit la fermer et avertir un agent de la surveillance.

Art. 157. — Des mesures doivent être prises pour que les portes normalement ouvertes, destinées à faire face à des éventualités particulières ne soient pas fermées intempestivement.

Art. 158. — Les portes qui sont sans objet, même temporairement, doivent être enlevées de leur gonds.

Art. 159. — Aucune modification ne doit être introduite dans les dispositions générales de l'aérage d'une mine sans l'ordre de l'ingénieur responsable de cet aérage; toutefois, en cas d'urgence, les agents de la surveillance peuvent prendre les mesures immédiates nécessaires, sous réserve d'en référer sans délai à cet ingénieur.

Chapitre III: Surveillance de l'aérage

Art. 160. — Le courant d'air général et les courants d'air éventuellement assujettis à un minimum de débit doivent être jaugés à des intervalles n'excédant pas trois mois dans des stations disposées à cet effet; ces jaugages doivent être également effectués après toute modification importante du régime de l'aérage.

Art. 161. — L'exploitant doit tenir sur le carreau de chaque siège:
  1) Un registre d'aérage où sont immédiatement inscrites à leur date les constatations méthodiques ou occasionnelles relatives à l'aérage;
  2) Un plan d'aérage indiquant notamment le sens des courants d'air, la situation des ventilateurs, des portes et des stations de jaugeage avec les débits mesurés à ces stations.
ANNEXE II

EXTRAITS DE LA REGLEMENTATION PARTICULIÈRE AUX MINES D'URANIUM

Art. 1er. — Sans préjudice de l'application des lois et règlements applicables aux mines et recherches de mine en général, la recherche et l'exploitation de mines sur des gisements de minerais radioactifs sont soumises aux règles ci-dessous concernant la protection du personnel contre les dangers propres à ces minerais.

Art. 2. — Aucun travail ne peut être effectué en fouilles ou tranchées, en puits ou galeries souterraines, creusés dans le minerai, radioactif ou communiquant avec d'autres parties creusées dans ce minerai, aucun stock de minerai radioactif ne peut être constitué, que conformément aux règles édictées par le présent arrêté.

I - EXPLOITATIONS SOUTERRAINES

Section A: Protection contre l'irradiation interne

Chapitre I: Aérage

Art. 3. — Tous les ouvrages souterrains accessibles aux ouvriers doivent être parcourus par un courant d'air régulier, aussi intense que possible, capable d'en assainir l'atmosphère à l'égard du radon et des poussières radioactives.

Art. 4. — La permanence d'un débit suffisant dans tous les circuits d'aérage doit être garantie par un ou plusieurs groupes moto-ventilateurs; dérogation peut être accordée par l'Ingénieur en chef des mines quand l'aérage naturel est reconnu suffisant.

Art. 5. — La moto-ventilation ne peut être arrêtée que suivant les conditions fixées par l'ingénieur de la mine.

Art. 6. — Tout arrêt accidentel d'un ventilateur principal doit être immédiatement signalé à l'ingénieur de la mine ou à son suppléant présent à la mine. Celui-ci doit prendre immédiatement les mesures nécessaires pour assurer la sécurité du personnel et faire, s'il y a lieu, évacuer la mine ou revêtir les appareils de protection individuelle prévus à l'article 28 ci-après.

Art. 7. — Après un chômage au cours duquel la ventilation principale mécanique a été suspendue ou réduite pendant plus d'un poste, les ouvriers ne doivent rentrer dans la mine que sur l'ordre de l'ingénieur de la mine et dans les conditions qu'il a fixées.

Si la ventilation principale a été arrêtée plus de trois jours, elle doit être rétablie au moins huit heures avant l'arrivée des premiers ouvriers.

Art. 8. — L'aérage des travaux non assainis par le courant d'air principal ou par l'une de ses dérivations doit être assuré par des engins de ventilation
auxiliaire. Une consigne de l'ingénieur de la mine fixe les conditions générales dans lesquelles ces engins sont installés, mis en marche, arrêtés ou enlevés.

Art. 9. — Avec ou sans remblai, l'exploitation doit être conduite de façon à garantir une bonne arrivée de l'air à front.

Art. 10. — Les travaux des étages dont l'exploitation est terminée ou abandonnée et qui pourraient occasionner des dangers, doivent être efficacement isolés des travaux en activité par des barrages étanches, ou être aérés.

Les barrages étanches prévus à l'alinea précédent ne peuvent être mis en place ou enlevés que sur l'ordre de l'ingénieur de la mine et sur ses instructions.

Art. 11. — Les eaux fortement chargées en radon doivent être canalisées aussitôt que possible. Elles ne doivent pas être utilisées dans la lutte contre les poussières.

Chapitre II: Contrôle

Art. 12. — Le courant d'air général, les courants d'air partiels en aérage primaire et les courants d'air secondaires doivent être jaugés à des intervalles n'excédant pas un mois; ces jaugages doivent être également effectués après toute modification importante du régime de l'aérage.

Les jaugages sont faits à l'entrée et à la sortie de la mine, à l'origine et à l'extrémité de chacune des dérivations du courant principal, immédiatement à l'amont et à l'aval de chaque chantier important ou groupe de chantiers.

Les résultats sont reportés sur un registre avec référence à un plan d'aérage. Une copie du plan d'aérage, accompagnée du relevé des contrôles les plus récents faits en exécution des articles 12, 13 et 14 est adressée à l'Ingénieur en chef des mines au début de chaque semestre, ainsi qu'après chaque modification importante au régime d'aérage.

DISCUSSION

R.L. ROCK: I would like to ask about your cyclones, as it was not quite clear to me how these operate. You mentioned a reduction in radon, could you clarify this?

Y. FRANÇOIS: In the system of back-filled stopes we use tailings sands which stem from the chemical plant. The portion of the sands having a particle size of less than 40 μm release 10 to 15 times more radon than the portion having a particle size greater than 40 μm. Hence the <40 μm portion is left at the bottom, and it is the portion with a particle size >40 μm which is used for hydraulic back-fill of the workings.

1 Les articles 13 et 14 concernent les contrôles de la concentration en radon et en poussières radioactives.
D.D. BELL: What was the covering on your bulkheads?
Y. FRANÇOIS: Most of the time we use a cement coating, but we carried out tests with an American apparatus which provides polyurethane foam. This has a slight disadvantage as you need a whole series of bulkheads over a shaft. In a cleaning operation, this is very hard on the budget!
C. PALMITER: Are you doing any research on the use of electrostatic precipitators for cleaning the air?
Y. FRANÇOIS: No, we have not yet done any, but studies are being considered.
G.R. YOURT: I am curious about your separation of the sands of the course, >40 μm particles from the <40 μm; I suspect you would get a carry-over attachment of fines together with the coarser sands and that you would get a considerable amount of emanation even from the classified tailings. Do you have any indication how this affects your ventilation?
Y. FRANÇOIS: No. Up to now we have had no problems when the cycloning was well done and, as I mentioned, we do not use particle sizes less than 40 μm for back-fill. I do agree that we must be very careful indeed, and I think that when the ore concentration increases we may have problems.
D.D. BELL: It is my understanding that some of your mines are not near your concentrators; how do you transport back-fill for these outside operations?
Y. FRANÇOIS: The distance between the mines and the processing plant varies from being close to the plant to being up to 30 km away. Transportation is by truck, and everything is carried out as if the truck was bringing ore and taking away tailings. The sands are packed in storage areas before being sent down the mine by different methods. In the case of small workings we use very simple methods.
G.R. YOURT: You mentioned a mean air flow of 1.5 m$^3$/s and I wonder if you could give a range of linear velocities in metres per second at an average range.
Y. FRANÇOIS: I have not done any averaging, but I think that it ought to be of the order of approximately 1 m/s in the main galleries. When we are in the main air returns, the velocity is much greater because there are less and less workings through which the air has to pass.
G.R. YOURT: If I understood you correctly, you mentioned a figure in the case of coal mining of 10 times the weight of air compared with tonnage of ore. What is the figure for the uranium mines?
Y. FRANÇOIS: 17 to 27.
G.R. YOURT: Excuse me for pursuing this, but I just want to get a good understanding of what your general ventilation system is. You use the general galleries for distribution, but do I understand you correctly—that the actual working places are ventilated by a secondary system, by fan and pipe?
Y. FRANÇOIS: Yes. All the working places have a secondary ventilation fan, but part of the primary air also passes to the working places at one or another point. If we solely used this primary air to provide the air current, we would not have sufficient sweeping or cleaning of all the parts of the workings. The secondary ventilation system enables us to send clean air to the working site occupied by the miners.
G.R. YOURT: Do you use any filters for cleaning your air?
Y. FRANÇOIS: This possibility is being studied. But since you mention filters, I am going to return to the question I asked you when I was speaking of apparatus for individual protection; I was thinking of using masks and oxygen devices in order to work a non-aerated zone. But, it seems, the use of personal protection apparatus has been eliminated; the use of plastic ducts, which can be rolled out to a great length in order to clean the atmosphere and to avoid the need for personal devices, is an improvement because, I do agree with you, it is very difficult to be quite certain that devices such as masks or hoods are going to be used at all.

F. E. McGINLEY (Chairman): I would like to ask a question about the application of computer calculations you mention in the paper. Are these just for this one specific mine, or are such calculations a general practice when estimating ventilation requirements and seeking to improve ventilation within the mines?

Y. FRANÇOIS: The computer calculations are used, in general, for all the CEA mines.
MINE ENGINEERING AND VENTILATION PROBLEMS UNIQUE TO THE CONTROL OF RADON DAUGHTERS

R. L. ROCK
EMS-Denver Technical Support Center,
United States Department of the Interior,
Denver, Colo.,
United States of America

Abstract

MINE ENGINEERING AND VENTILATION PROBLEMS UNIQUE TO THE CONTROL OF RADON DAUGHTERS.

Quality and quantity of ventilation are the two interrelated but key factors in any radon-daughter control programme. The better the intake air quality (little or no contamination from radon and its daughters), the less are the total air requirements for ventilation of active mining areas. Engineering principles for quantity distribution of air through underground working areas are straightforward and the formulae and theories governing forced ventilation are not within the scope of this paper. Rather, this paper discusses the principal methods of utilizing mine planning to facilitate radon-daughter control and also treats the more subtle features of mine ventilation which are especially critical in the ventilation of mines where radon gas constitutes an environmental contamination problem.

INTRODUCTION

Mine design and ore handling methods inevitably affect the relative difficulties encountered in controlling underground radon daughter concentrations. The reason this is true is that these two features influence both the effectiveness of mechanical ventilation and the influx of radioactive contaminants into active mine areas. The generation of radon and its short-lived daughter products cannot be prevented, but the deleterious effects can be largely controlled through systematic arrangement of the mining sequence relative to ventilation patterns.

MINE PLANNING

Obviously, little successful mine planning can be accomplished without reasonably accurate knowledge of both the spatial orientation and physical characteristics of the ore. Unfortunately uranium mines are notoriously difficult to delineate by drilling. Drilling on even 25-feet centers may yield an inaccurate picture of the orientation, continuity, quality, and quantity of ore to be mined.

Ideally, to allow maximum utilization of mine planning for radiation control purposes, ore should be delineated as thoroughly as practical by surface exploration before mining is commenced. Once the extent and configuration of the ore is known, the best mine layout for efficient ore extraction is usually quite obvious. However, mine layout to obtain maximum radon-daughter control may not be quite so apparent to the uninitiated.
Several years ago I was responsible for an exploration-development drilling program in an area in which there was no prior experience regarding ore deposition. As it turned out, the uranium values were concentrated in nearly vertical fractures occurring 10 to 20 feet apart. When drilling for developmental purposes, the drill bit repeatedly intersected one of these closely spaced fractures and, because of relative rock hardness, tended to follow the plane of the fracture. Although the intervening ground between fractures was well mineralized, it was not nearly so high grade in uranium as was inferred from radiometric and chemical analyses of the drill cuttings. The mining of this particular deposit was profitable, but not to the extent that it could have been if mining and ventilation had not had to be readapted to accommodate the unanticipated mode of ore occurrence. Later development drilling in the vicinity of the first ore body was designed to transect fracture zones to reveal the true nature of the intervening rock.

Figure 1 shows a simplified and idealistic mine layout for three disconnected ore deposits aligned in a somewhat linear fashion. The development openings and mining sequence depicted are designed both to enhance ore extraction efficiency.

FIG. 1. Plan drawing of an idealized developmental method for mining multiple uranium deposits to facilitate control over radon daughters.
Method advantages: (1) Short haulageways and air courses, (2) production and a second escapeway are achieved quickly, (3) contamination of intake air is prevented, (4) air can easily be shunted between No. 2 and No. 3 ore bodies.
and to allow radon-daughter control with a minimum amount of ventilation. The important thing mine operators must remember is that radon-daughter control is an undeniable mining cost just as ground control, rock breakage, and ore handling are.

Desirable principles of the development system shown in figure 1 are short haulageways and air courses, the ability to achieve rapid production, and the early provision of a second exit from the mine. Contamination of intake air is precluded and the system is flexible so that available intake air can readily be shunted between ore bodies as air requirements change. Note also that all mined-out areas are kept on the return-air side of the system and that the main operating shaft and haulageway serve as intake airways. The latter feature prevents routine exposure of haulageway workers to high radiation levels inherent in return airways.

Many factors other than inadequate ore delineation can influence the operator’s ability to use mine planning for radiation control. Financial pressures sometimes are responsible for mine managers abandoning sound mining plans for expedient methods of achieving increased production. In other instances plain short-sightedness is the apparent cause.

A problem being encountered today is that relative “low-uranium, high-vanadium” mines are being rehabilitated for mining vanadium, which has become lucrative on today’s market. Rehabilitation of old mines nearly always entails special ventilation problems and the potential advantages of mine planning are precluded.

The radiation control problems of newly developed mines almost always arise from mining on the advance without providing a means of diverting the resulting radioactive contaminants from working places in the ventilation currents downwind. Extensive underground exploration drifting may be practiced on the advance in which each and every ore lead is followed diligently. Because such exploration drifts are most often sinuous and explicitly designed to expose as much ore as possible, they not only create contamination problems but also provide very inefficient ventilation openings. Long-hole underground exploration drilling is a better practice than exploration drifting, but ore discovered in this way is also difficult to integrate into a systematic mining plan.

Main development openings and secondary haulageways may be driven in the ore horizon, but sublevel developmental systems are preferable for the primary intake airways and primary haulageways.

United States uranium mines developed within the last few years show evidence that considerable thought is being given to the economics of radon-daughter control. The larger the ore deposit and longer-lived the operation, the more economic advantages there are to be reaped from proper mine planning. Unlike methane, radon gas does not bleed off with time; contamination sources (mineralized rock) exposed in early
mine developmental stages create an added burden on the ventilation system throughout the life of the mine. Where a mine is operated 20 to 30 years, unnecessary contamination burdens on the ventilation system could easily add hundreds of thousands of dollars to composite ventilation costs.

Although all of the principles of mine planning which favor radon-daughter control may not be applicable in any one instance, the principles should be understood so that they can be applied effectively wherever practical.

Reiterating these principles in order of importance:

1. Development openings serving as intake airways should be driven in barren ground. If ore or protore is inadvertently penetrated, it should not be mined on the advance.

2. Mined-out areas should be maintained on the return-air side of the ventilation system in so far as practical. The name of the game is to avoid having the contamination from non-productive areas add to the contamination woes of active areas.

3. Minimize the number and size of development openings connecting intake airways to active mining sections in order to facilitate later "sealing-off" of mined-out sections.

4. Design the mine so that main haulageways, hoisting stations, and other areas essential to routine production and maintenance (except for facilities which may constitute fire or explosive hazards) are in intake airways.

Obviously mining methods, such as shrinkage stoping, which require the storage of large tonnages of broken ore underground, are not in the best interests of limiting the amount of radon released into the mine environment. For rock containing a given amount of Ra\textsubscript{226}, radon is generated at a constant rate. The amount of radon emanated from the same rock into the mine atmosphere, however, is proportional to the surface area of the rock. This also explains why the practice of backfilling mined-out areas with protore or mill tailings containing Ra\textsubscript{226} greatly increases the potential radon contamination problem, unless, of course, such filled stopes can be positively isolated from ventilation to active mine areas.

One ore handling problem which is seldom recognized is ore spillage along intake airways. From my observations, radon contamination from ore spillage is much more of a problem where trackless haulage is employed. Spillage is generally related to roadway conditions, condition of haulage vehicles, travel speeds, and overloading of haulage vehicles. Over a period of time, radon contamination from accumulated ore spillage can become significant.
In one instance where an intake airway was converted from trackless haulage to track haulage, protore was used to fill low spots along the haulageway and to provide the uniform grade needed for track installation. Although the operator knew that in-place ore was not exposed by the haulageway, he found that the intake air (about 30,000 ft³/min) was contaminated to 2.0 working levels before it reached the first active mining area. The problem was very perplexing until we discovered the actual source of the contamination.

Loads of protore are often dumped into low spots along trackless haulageways to improve the drainage of ground water.

Ground water itself is a known carrier of dissolved radon but, except under unusual conditions, e.g. high rates of water flow through rocks of high porosity and relatively low permeability, the added radon contribution due to the presence of ground water is usually quite low. Water under high hydrostatic pressure is capable of transporting much more radon from its point of origin within the rock to mine openings than would otherwise occur through regular diffusion processes. Ground water flowing through open drainage ditches in intake airways can release significant radon into the mine environment unless the water has been previously purged of radon when it first percolated into mine openings. In all likelihood, most dissolved radon is released immediately to the air as the water seeps into mine openings. The percentage of radon released depends on temperatures, pressures, and concentration gradients between radon in water and radon in air. We know of a few mines where ground water is the sole transporter of radon into the mine environment. Contamination control in these circumstances must be directed at isolating the flow of water from the primary intake air system.

VENTILATION

The general engineering principles for the design of a well-organized ventilation system are the same for radioactive mines as for mines which extract non-radioactive materials. The main difference is that more discipline must be applied to the more subtle aspects of good ventilating practices. Inefficiencies in ventilation are readily discernible through increased radioactivity. In fact, one author has suggested that an improved method for evaluating the ventilation systems of non-radioactive mines might be to inject radon into the system and use radiation measurements to determine the relative efficacy of air distribution. A more practical application for artificially induced radon might be to inject it behind mine seals to allow radiometric detection and tracing of critical leakage which may be occurring.

The added ventilating-practice disciplines required for efficient radon-daughter control are all related to the fact that the health hazard increases with elapsed time following contamination of the environment by radon. Therefore, any factors which disrupt or retard the air-exchange process are to be avoided as much as possible.
General Ventilation Principles

The first engineering feature which should be sought in the ventilation of radioactive mines is the provision of adequate cross-sectional area mine openings suitable to provide for the passage of adequate quantities of intake and return air. Size and uniformity of openings should preclude the need for excessive air velocities and air pressures. This may sound basic, but all too often this simple concept is ignored. High fan pressures require high power costs and usually result in high air velocities. High air velocities can cause the freezing of air and water lines, much miner discomfort, and, in some cases, increase the silica dust hazard.

Air recirculation is actually pseudo ventilation which may not only be ineffectual (depending upon degree) in controlling radon daughters but also sometimes creates worse situations than would arise with natural ventilation. Air recirculation may take many forms. Probably the most common forms are recirculation within and between secondary systems. The former is usually caused by inappropriate location of the fan inlet relative to the primary air supply. If the fan inlet is not located well upstream in the primary air supply, recirculation frequently occurs. Recirculation between secondary systems is tolerable only where the primary air quantity is great enough to dilute the contaminated air from the first system sufficiently to allow the air to be reusable by the second system. Of course, the primary air supply must exceed the capacity of the auxiliary fan or fans or recirculation is inevitable.

Recirculation within the primary system is most often caused by leaky booster fan bulkheads or by leaky stoppings installed to separate intake airways from return airways. More subtle primary recirculation occurs where intake airways are, in part, large open stopes having large cross-sectional areas. In this instance, air velocities become so low due to a lack of airflow confinement that convection currents and natural draft pressures cause a good portion of the air to move aimlessly.

The same thing can happen where large active stopes are ventilated without the provision of adequate air-control corridors to distribute the air undirectionally and uniformly through the stoping area. Sometimes, due to marked density differences, a distinct channeling of the intake air will occur through such large open stopes. When this happens, peripheral stope areas undergo a very slow air-exchange process allowing high radon-daughter concentrations to develop outside the main channel of airflow. Due to air entrainment, these high radon-daughter concentrations are gradually drawn into the main airflow causing higher overall radon-daughter concentrations to prevail than if the total airflow were more uniformly distributed throughout the entire stope.

An interesting aspect of ventilating mines for the control of radon daughters is that dead-end barren side-drifts and similar openings connected to intake airways can have a
FIG. 2. Influence on radon-daughter concentrations owing to proper and improper sealing.

The importance of uniform ventilation and non-leaking seals is illustrated. If seals are not designed to preclude the entrance of contaminated air into intake air they are actually detrimental to radon-daughter control. All calculations assume uniform radon emanation throughout exposed mine surface areas and are based on the following equation:

\[ V_2 = V_1 \left( \frac{W_{L1}}{W_{L2}} \right)^{0.36} \]

where

- \( V_2 \) = ventilation in ft\(^3\)/min (cfm in the figure) after quantity changes have been made
- \( V_1 \) = initial ventilation in ft\(^3\)/min (cfm in the figure)
- \( W_{L1} \) = measured working level in \( V_1 \)
- \( W_{L2} \) = measured working level in \( V_2 \)

decidedly harmful effect on radiation control even though the side-openings themselves do not emanate radon. The effect of such side-openings is to provide a delay volume which is filled with the radon-contaminated air from the connecting airway by diffusion and convection processes. The resulting radon-daughter growth time within the side-opening allows the development of near equilibrium between radon and its daughters. This relatively high contamination is then gradually fed back into the main ventilating system as the convection and diffusion process proceeds. Such side-openings are seldom sealed, but under some circumstances, sealing would be helpful.

Sealing of mined-out areas is a common practice to attempt to prevent radon and its daughters generated therein from contaminating active mine areas. Unfortunately most sealing projects are not very effective and some even add to the control problem. Figure 2 shows the relative effects of a perfect seal vs. imperfect sealing. In reality, the radon
permeability resistance of the coating material used on seals is not nearly so important as the need to make the seal as airtight as practical. Because seals cannot be made absolutely airtight, they must be provided with a negative pressure behind them to assure that the leakage which invariably occurs is "into" and not "out from" the sealed area. Negative pressure behind seals is usually provided by high-pressure low-volume fans mounted on the surface exhausting from boreholes penetrating the sealed area.

All radioactive mines should be ventilated with a mechanical system even though during certain periods of the year natural draft pressures may provide more ventilation than is provided solely by the mechanical system. Both directional and quantitative control over ventilation are absolutely essential to the continuity of any radon-daughter control program. Natural ventilation cannot be relied upon for either directional or quantitative control over airflow and does not provide an acceptable method of ventilating. Natural draft pressures can, however, sometimes be integrated advantageously into the total system.

Uranium mines and other radioactive mines having ventilation systems of any complexity should avoid discontinuing ventilation between active shifts. The growth of daughters underground over an 8-to 16-hour period without ventilation can require a considerable amount of time to be nullified after ventilation is resumed. High worker exposures can therefore occur over an indefinite interim period after ventilation is restored. The amount of time required for environmental control over radon daughters to be reestablished depends upon how quickly ventilation causes a complete change of underground air to occur.

Ventilation engineers presently make extensive use of boreholes for ventilation of U.S. uranium mines. Usually the main intake airway is the operating shaft, and return airways are boreholes dispersed throughout the ore body so that major mining sections are each provided with a separate split of intake air. This system has generally worked quite well. If a mining section presents a particularly difficult ventilation problem, that particular section is sometimes isolated from the rest of the ventilation system by providing the section with its own intake and return air boreholes. A distinct advantage of the split system of ventilating is that only that volume of air required to ventilate each mining section need be passed through it. This is in direct contrast to a series ventilation system in which the quantity of air required for the working place most difficult to ventilate must be passed through the entire system. Another obvious advantage of the split system of ventilation is that radioactive contaminants are not cumulative throughout the system. Instances where ventilation requirements have become prohibitive are usually the result of the mine operator's reliance upon extensive series ventilation.

Air Quantities Required

Air quantities required for radon-daughter control usually exceed air requirements for the control of conventional
contaminants such as blasting gases, diesel exhaust gases and dusts; but air quantity requirements need not be excessive if excessive series ventilation is not practiced. Formulas are available for calculating air quantities necessary to control specific radiation-ventilation conditions, but the data needed to make these formulas valuable is often elusive. So long as the intake air can be delivered to the mining faces relatively free of contamination, 2000 ft³/min of air will do a good job of ventilating a 10-ft × 10-ft face of high-grade ore. As the intake air becomes contaminated above 0.1 working level, however, air quantities required for control increase rapidly. Figure 3 shows the factors by which air quantities needed for control increase as the intake air becomes contaminated.

Maintenance

Maintenance of ventilation systems plays an important part in determining the radiation exposures that underground workers ultimately experience. No matter how well planned and installed the ventilation system is initially, the system must be maintained or efficiency rapidly deteriorates. Maintenance is often badly neglected, especially where a ventilation engineer or some other knowledgeable person familiar with the radiation hazard is not assigned direct responsibility for maintaining adequate ventilation. Persons assigned this responsibility must be willing to apply themselves fully to the problem and must have authority to make the corrections or repairs to the ventilation system necessary to maintain healthful conditions.
Control of radon daughters in radioactive mines is sometimes considered to be basically a ventilation problem. The problem is, however, of such a nature that control over the amount of contamination released into the mine environment plus control over the manner in which that contamination is removed from the mine environment relative to occupied mine areas are of major importance in determining the difficulty of the ventilation problem.

In many respects, the radon-daughter control problem is unlike the problem of controlling any other mine environmental contaminant. One reason this is true is because of the rapid growth of the hazard (radon daughters) following contamination of the air with the parent radon. Another reason is that so few atoms of radon emanating from so many different sources can be involved in total mine contamination problems.

I have worked on ventilation problems involving dust, blasting gases, diesel exhaust gases, and methane and I believe that solutions to radon-daughter problems require much more finesse than any of these other problems.

The only satisfactory method which I have found to provide practical solutions to radon-daughter problems is to first make a detailed assessment of contamination sources relative to existing air distribution. Detection of subtle contamination causes may require highly trained personnel using specialized equipment. Usually the mine must be considered in its entirety during the contamination assessment program. Answers sought are:

1. Where and why major contamination problems are occurring.
2. How beneficial changes may be affected without causing harmful effects in other active mine areas.
3. What major changes, such as increased primary airflow, are necessary to assure long-range environmental control over radiation levels.

Far too many mine operators try to solve their radiation problems by the indiscriminate addition of more primary ventilation. Increased air quantity is often necessary, but, for maximum effectiveness, additional air must be integrated appropriately into the ventilation system. The only way this integration can be accomplished with any degree of certainty of success is through utilization of information gathered in preliminary detailed radiation-ventilation surveys. Such surveys are time-consuming in that they require measuring air quantities and associated radiation in all the separate branches of the ventilation system.

We have found from the radiation-ventilation surveys conducted by our group that, in a surprising number of instances,
satisfactory radon-daughter control is attainable merely by containment and/or diversion of contamination emanating from inactive mine areas.

BIBLIOGRAPHY


DISCUSSION

S. R. AUSTIN: I wonder if Mr. Rock would be willing to modify a statement in his paper in which he says the amount of radon emanating from a certain rock into the mine atmosphere is proportional to the surface area of the rock. I think this is a first approximation only. I believe that the amount of radon emanated is related to many different parameters, but perhaps more closely to the surface area of the contained uranium mineral than to the surface area of the rock.

R. L. ROCK: I suggest that this is a technicality. Of course, I was speaking of a uniform mineral surface area, but I do understand your contention.

G. R. YOURT: I wondered to what extent in your surveys do the operators request assistance in improving the ventilation?

R. L. ROCK: We get a considerable number. We are not deluged with requests, but I think most of the operators have been pleased with our work. Usually we can do a lot of good without any appreciable expense, just by rearranging what the operator already has. It is surprising how much good you can do just by putting everything down on paper to see how you can rearrange things.

G. R. YOURT: Do supervisors go around with you when you are taking samples?

R. L. ROCK: Yes they do. This is one really valuable thing; even if we do not succeed in curing anything, they at least take a look and see the problems that we see. The miners incidentally are very interested. In the early days they never even wondered what we were doing, but now they almost always ask what the situation looks like and what the concentration is. In the Uravan mineral belt, almost all of them know someone who has died, so they are well aware of the problem: they are concerned.

D. D. BELL: I was wondering if you have ever faced the problem of the escape way being in waste exhaust air, with high radon counts?

R. L. ROCK: Of course we would rather have the waste exhaust air in the escape way than in the main operating opening where the men spend
most of their time. In United States mines, the intake air system is usually common with main operating haulage-ways and hoisting compartments.

D.D. BELL: Is there anything in the mine regulations for inspection that specifies certain radiation levels in exhaust airways that are also escape ways?

R.L. ROCK: No, not unless they are occupied.

P. ZETTWOOG: Could you tell me whether the help that you are giving is subsidized by the Department of the Interior or by the operator himself?

R.L. ROCK: The surveys were made by the Government, by the Department of the Interior. The operator pays nothing.

S.R. AUSTIN: I think you mentioned placing your haulage-ways in waste rock, which is of course an effective way of controlling radon. However, I think that in the United States uranium mines the so-called waste rock will still contain some uranium, and I wonder what your experience has been on build-up of radon in haulage-ways in this type of rock.

R.L. ROCK: The problem is whether there is time for the radon emanation to get to the working place. Again it's the same old time versus emanation problem.

G.R. YOURT: Is the use of filters increasing or decreasing?

R.L. ROCK: It is decreasing; we do have a few in use, such as static precipitators. One company, at considerable expense, bought quite a few but for some reason they are not utilizing them a great deal. The equipment has been giving them problems because it requires considerable maintenance. The filters do a wonderful job in removing the radon daughters, but of course you have still got the radon. I think this air cleaning is just an expedient method of taking care of part of the problem where you have no other solution. It is never going to be part of a real planned control system.

R.H. KENNEDY: Do you think that the radiation control problems have been the primary cause of the closing down of any substantial number of mines in the Uravan belt?

R.L. ROCK: No; I feel very strongly that this has had a minimal effect on closures. I think the closures were pre-ordained because of the slump in the market.

F.E. McGINLEY (Chairman): I would like to ask Mr. Rock about the use of polyurethane foam coatings on the stoppings, which was mentioned in the course of the meeting. Would you care to comment on the effectiveness of this foam-type of coating as you have seen it used in the United States uranium mines?

R.L. ROCK: It is a very effective coating; because of its expansion you can fill large voids handily. It does, however, create a fire hazard if you get too thick a layer. I know of three mines where spontaneous fires resulted from putting on too great a thickness. It is also expensive, and the mixture has to be 'just right' or you don't get the ideal cellular composition; it is a good sealer when used properly.

R.H. KENNEDY: What do you find to be the most satisfactory method of sealing?

R.L. ROCK: Sealing itself is not nearly as critical a problem as providing a negative pressure behind a bulkhead so that all leakage is inwards. You can manage adequately with a polyethylene stopping with a negative pressure behind it. You do not need a masonry stopping or even an asphalt-type of coating. I would say polyethylene supported on a framework is common.
D.D. BELL: It is not practical in many instances to build bulkheads because you cannot get negative pressures behind them; the building of the bulkhead only increases your problem with the build-up of radon gas behind it. I sometimes wonder whether it isn't better to leave some of these dead-ends open and ventilate them.

R.L. ROCK: You are absolutely correct, unless you can provide the negative pressure. We have so many open exploration bore-holes in our rather shallow mines that it is easy to arrange a fan to provide a negative pressure in the sealed volume.

F. E. McGINLEY (Chairman): Mr. Goodwin called to my attention that in 1972 there was an air-cleaning conference held in the United States of America, at which he presented a paper which he has offered to make available to members of the Panel. A part of the air-cleaning conference dealt specifically with the cleaning of air in uranium mines. For the benefit of the Panel, Mr. Goodwin could perhaps tell us how the subject was covered and what papers or reports are available.

A. GOODWIN: The conference was the 12th (United States) AEC Air-Cleaning Conference and only a small part of the meeting was concerned with cleaning air in uranium mines. There was a session on uranium mines which was chaired by Mr. Breslin of the Health and Safety Laboratory in New York. There were three papers: Mr. Rock presented one entitled "Control of radon daughters in U.S. underground uranium mines". The second paper, presented by Mr. Washington of the Mining Research Center, Elliot Lake, Ontario, Canada, was entitled "The use of Vermiculite to control dust in radon daughters in underground uranium mine air". My paper was called "Review of problems and techniques for removal of radon and radon daughter products from mine atmospheres". Mr. Rock's paper was primarily concerned with mine ventilation, Mr. Washington reviewed some experiments that he conducted in Canada using Vermiculite as a filter medium, and he gave a number of interesting experimental measurements he had made and experimental design analysis of these experiments. He determined the efficiency of removing both dust and radon daughters as a function of thickness of the filter bed and face velocity. The paper which I presented contained a summary of ideas from the literature with respect to a variety of air-cleaning concepts. I tried to review what might have to be done in the way of air cleaning to remove both radon daughters and radon gas. The problem of removing radon gas is a much more difficult technological problem and no one has really done that in a uranium mine except by ventilation. Without going into details, some of the methods for removing radon are use of a gas centrifuge, cryogenic methods, chemical removal and, of course, adsorption into charcoal beds. All these methods present difficulties, and there are many technological problems to solve before any can be of practical value in uranium mine air cleaning.
SUMMARY REPORT ON SESSION 2

TECHNICAL PROBLEMS OF URANIUM MINE VENTILATION

Introduction

Properly designed ventilation systems are imperative in underground mining of uranium to prevent over-exposure of workers to radon progeny. The importance of detailed mine planning and continuous surveillance of ventilation systems was emphasized. The three papers describing practices in Canada, France and the USA revealed striking similarities which are summarized.

Ventilation

In many respects the control of alpha radioactivity in mine atmospheres can be achieved by applying methods used for controlling other airborne contaminants such as dust, diesel exhausts, blasting gases and methane. This is done by suppressing, confining, diluting and removing the contaminants. However, some additional problems and phenomena are encountered in uranium mines which require special control measures.

As the radon gas emanates into the mine atmosphere the concentration of radioactivity increases significantly with time which means that it must be removed quickly. This requires higher velocities and consequently larger volumes of air flow through working places and increases the cost of control measures substantially, especially if the air must be heated during winter.

Primary ventilation consists of getting the fresh air into the mine and the used air out of the mine. All working places are served by the secondary ventilation system which distributes the fresh air to production and development areas. Some difficulties are encountered in properly ventilating various types of working places, such as sub-level development drifts, reinforced stopes and storage chambers.

Computer calculations are used in France for designing effective primary ventilating systems for underground uranium mines. Constant surveillance of the ventilation is maintained by a separate team with no responsibility for production problems.

Uranium mines having ventilation systems of any complexity should avoid discontinuing ventilation between active shifts because the growth of radon daughters can require considerable time for removal or dilution after ventilation is resumed.

Mine planning

Mine design and ore handling methods inevitably affect the relative difficulties encountered in controlling underground radon-daughter concentrations. To allow maximum utilization of mine planning for radiation control purposes, ore should be delineated as thoroughly as practical before mining is commenced.

Desirable principles of the mine developmental system are as follows:

(a) Development openings serving as intake airways should be driven in barren ground. If ore or protore is inadvertently penetrated, it should not be mined on the advance.
(b) Mined-out areas should be maintained on the return-air side of the ventilation system as far as practical.

(c) The number and size of development openings connecting intake airways to active mining sections should be minimized in order to facilitate later 'sealing-off' of mined-out sections if it becomes necessary.

(d) The mine should be designed so that main haulage-ways, hoisting stations, and other areas essential to routine production and maintenance (except for facilities which may constitute fire or explosive hazards) are in intake airways.

Mining methods, such as shrinkage stoping, which require the storage of large tonnages of broken ore underground, should be avoided whenever practical.

Sealing of mined-out areas is a common practice to prevent radon and its daughters generated therein from contaminating active mine areas. Unfortunately, most sealing projects are not very effective; therefore, negative pressure behind seals is usually provided by high-pressure low-volume fans mounted on the surface exhausting from boreholes penetrating the sealed areas.

Ground-water is a known carrier of dissolved radon and, if it appears, such water could introduce a significant quantity of radon. Control should be directed at isolating the flow of water from the primary intake air system.

Mine backfilling with coarse tailing material has been successfully used in France, and for the more distant mines ore trucks haul tailings on the return trips.

Instrumentation

There is a great need for research and improvements in instrumentation for on-the-spot measurement of radioactivity to enable prompt corrective action and for a more accurate assessment of cumulative exposure.
RESEARCH ON MODE OF RADON RELEASE
BY DIFFERENT TYPES OF ORE BODY

(Session 3)
RADON-222 EMANATION CHARACTERISTICS OF ROCKS AND MINERALS

P. M. C. BARRETTO
National Nuclear Energy Commission,
Rio de Janeiro, Brazil

Abstract

RADON-222 EMANATION CHARACTERISTICS OF ROCKS AND MINERALS.

The activity, emanation rate and percentage of radon-222 escape were investigated for a variety of rocks and minerals using alpha scintillation counting techniques. Rocks show a wide range of leakage with values ranging from 1 to 20% and an activity of 2 to 80 x 10^4 pCi/h·g under identical laboratory conditions. The stronger emanations were found among granitic rocks and conglomerates whereas basic and calcareous rocks showed the lowest values. Accessory minerals, although rich in uranium, show very low radon emanation, i.e., less than 1 to 2%. The lack of dependence of emanation on parent uranium concentrations was clearly established. A positive correlation was observed between weathering and radon escape and between natural alpha dose and emanation. High-temperature experiments (up to 1200°C) on minerals demonstrated a progressive decrease in the percentage of radon loss. This phenomenon appears to be the result of annealing of natural radiation damage. As expected, an increasing radon loss with decreasing particle size was observed. The temperature dependence of radon emanation in the range of -80°C to +250°C was investigated and showed a strong adsorption for temperatures below -20°C.

1. INTRODUCTION

Radon escape from radioactive minerals was first noted in the early years of this century. Boltwood [1-3] in his study of the origin of the radium introduced the term 'emanating power' to describe the loss of emanation from radioactive minerals. Lind and Whittemore [4], investigating the radium-uranium ratio in carnotites found 'emanating power' ranging from 16 to 50%. Fyhn [5] observed that the emanation from brøggerite increased with decreasing particle size.

Other studies of radon emanation from uranium-rich minerals have been reported by Holmes [6], Giletti and Kulp [7], and Kulp et al. [8]. However, data on emanation from common rocks and soils are very scarce in the literature, probably because of the small amount of radon atoms produced and consequently their difficulty in detection. With the development of alpha scintillators combined with multiplier phototube techniques, the sensitivity limit problem was greatly reduced. In fact, this has become one of the most sensitive laboratory techniques in inorganic analytical chemistry, exceeding the sensitivities of conventional mass spectrometers.

The 3.82-d half-life of 222Rn produced from 226Ra in soils and rocks permits extensive migration of radon in the natural environment if the radon can escape from its production site in the mineral. A review of radon migration in the ground and ground-water is given by Tanner [9, 10]. Wind and barometric pressures cause an important fraction of this free radon to disperse from the soil interstices and rock fractures into the atmosphere (Moses et al. [11]; Wilkening and Hand [12]; Foote [13]; Kraner et al. [14]; Schroeder et al. [15]; Gold et al. [16]; Pearson and Jones [17]; Lucas and Gabrysh [18]; Blanchard [19]; Pohl-Rüling and Pohl [20]; and many others, as literature on radon in the atmosphere and hydrosphere is abundant).
2. LABORATORY PROCEDURES AND TECHNIQUES

2.1. Sample preparation

Rock samples were crushed and sieved with care to avoid mineral separation. A grain size of -60 to +115 mesh was used in most measurements for the purpose of comparing results under similar conditions. However, rock samples obtained as powdered material were analysed as received. All samples with unknown uranium content were analysed for potassium, uranium and thorium by gamma-ray spectrometry as described by Adams [21]. This gamma-spectrometric method determines $^{238}$U equivalents (reported as eU, measuring the 1.76-MeV photons from $^{214}$Bi). For the purposes of this study, this determination of $^{214}$Bi, a prompt daughter of $^{222}$Rn, is particularly satisfactory because it is independent of whether or not there is secular equilibrium between parent $^{238}$U and all the intermediate daughters down to $^{226}$Ra.

2.2. Laboratory technique

To measure the naturally escaping fraction of gas produced within the crystals, it should be disturbed as little as possible; thus any chemical treatment or gas-sweeping type of radon collection could not be used. To avoid this problem, a volume-sharing type of transfer was used. The technique is described in detail by Barretto [22] and briefly summarized here. Initially a sample was sealed at atmospheric pressure in a glass

![Schematic diagram of transfer system.](image)
flask and allowed to de-emanate for approximately 8-10 d. The flask was then connected to an alpha-counting scintillation chamber, and the gas containing the accumulated radon allowed to equilibrate within the system for about 2 min.

For the present analyses, two volume ratios were used according to the sample weight or activity, transferring approximately 38 or 65% of the radon to the alpha counter. The intrinsic alpha-counting efficiency is 84% (Lucas [23]).

Figure 1 is a schematic diagram of the transfer system. Four hours after the transfer, the decay rate within the chamber was determined.

The statistical uncertainty in the events, $\sigma$, is given by the expression $\sqrt{NJ}$ (Lucas and Woodward [24]), where $N$ is the mean number of observed counts and $J = \sigma^2/\mu$, the variance in the number of counts from one family, i.e. radon parent plus daughters divided by the mean number of observed counts per family. The average error attributable to the counting statistics alone is approximately ±8%. A larger error is introduced through dependence on gamma-ray spectrometric determination of uranium equivalents. Hence the total error may range from 15 to 30% for the uranium-low materials. For the zircon and sphenes concentrates the uranium concentrations are known at ±1% (isotopic dilution). Thus, assuming radioactive equilibrium between $^{238}\text{U}$ and $^{226}\text{Ra}$, the errors are in the total order of 2-8%.

Calibration checks and counter background evaluations were performed prior to every analysis and several blanks were run during the experiments. An increase in the background with time of use was observed in all counters. All data were reduced by computer.

![Radon escape from rocks](FIG. 2)
FIG. 3. Radon activity in rocks.

FIG. 4. Radon escape from minerals.
### TABLE I. RADON EMANATION CHARACTERISTICS - ROCKS

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>ROCK TYPE</th>
<th>eU (ppm)</th>
<th>222Rn ACTIVITY (10^4 pCi/h-g)</th>
<th>EMANATION RATE (at. Rn/h-g)</th>
<th>ESCAPE-TO-PRODUCTION RATE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEB-427</td>
<td>Gneiss</td>
<td>0.6</td>
<td>2.26</td>
<td>4.0</td>
<td>14.0 ± 0.76</td>
</tr>
<tr>
<td>VCH-34</td>
<td>Gneiss</td>
<td>0.4</td>
<td>0.14</td>
<td>0.2</td>
<td>1.0 ± 0.26</td>
</tr>
<tr>
<td>I-275A*</td>
<td>Ots-monz-gneiss</td>
<td>11.9</td>
<td>7.27</td>
<td>12.8</td>
<td>2.4 ± 0.08</td>
</tr>
<tr>
<td>E-D-3</td>
<td>Ots-monz. orthgneiss</td>
<td>1.7</td>
<td>5.41</td>
<td>9.5</td>
<td>7.6 ± 0.90</td>
</tr>
<tr>
<td>E-829*</td>
<td>Ots-dior. paragneiss</td>
<td>4.0</td>
<td>8.26</td>
<td>14.5</td>
<td>7.9 ± 0.82</td>
</tr>
<tr>
<td>E-830*</td>
<td>Granodiorite</td>
<td>2.3</td>
<td>9.81</td>
<td>17.3</td>
<td>16.9 ± 0.19</td>
</tr>
<tr>
<td>E-827*</td>
<td>Granodiorite</td>
<td>2.0</td>
<td>20.20</td>
<td>35.6</td>
<td>40.0 ± 3.1</td>
</tr>
<tr>
<td>VOB-22</td>
<td>Granodiorite</td>
<td>1.9</td>
<td>1.85</td>
<td>3.1</td>
<td>3.9 ± 0.16</td>
</tr>
<tr>
<td>VOB-20</td>
<td>Granodiorite</td>
<td>1.6</td>
<td>4.92</td>
<td>8.7</td>
<td>12.2 ± 1.28</td>
</tr>
<tr>
<td>VOB-29</td>
<td>Ots. diorite</td>
<td>0.6</td>
<td>1.07</td>
<td>1.9</td>
<td>4.7 ± 0.87</td>
</tr>
<tr>
<td>VOB-171</td>
<td>Ots. diorite</td>
<td>3.2</td>
<td>4.76</td>
<td>8.7</td>
<td>6.1 ± 0.97</td>
</tr>
<tr>
<td>E-832*</td>
<td>Ots. monzonite</td>
<td>3.0</td>
<td>6.98</td>
<td>12.3</td>
<td>9.2 ± 0.33</td>
</tr>
<tr>
<td>VBE-405</td>
<td>granite</td>
<td>0.9</td>
<td>1.56</td>
<td>2.7</td>
<td>6.0 ± 0.91</td>
</tr>
<tr>
<td>VOB-173</td>
<td>granite</td>
<td>1.0</td>
<td>3.69</td>
<td>6.5</td>
<td>15.4 ± 2.2</td>
</tr>
<tr>
<td>VEB-460</td>
<td>Granite</td>
<td>3.0</td>
<td>28.80</td>
<td>43.7</td>
<td>32.7 ± 1.3</td>
</tr>
<tr>
<td>VEB-76</td>
<td>Pegmatite</td>
<td>7.8</td>
<td>9.48</td>
<td>14.9</td>
<td>4.3 ± 0.15</td>
</tr>
<tr>
<td>I-262*</td>
<td>Pegmatite</td>
<td>14.4</td>
<td>11.00</td>
<td>19.4</td>
<td>3.0 ± 0.30</td>
</tr>
<tr>
<td>E-721*</td>
<td>Porph. granite</td>
<td>24.6</td>
<td>46.30</td>
<td>78.7</td>
<td>12.5 ± 0.28</td>
</tr>
<tr>
<td>E-820*</td>
<td>Granite</td>
<td>6.1</td>
<td>62.20</td>
<td>109.5</td>
<td>40.4 ± 2.7</td>
</tr>
<tr>
<td>E-831*</td>
<td>Granite</td>
<td>1.9</td>
<td>4.53</td>
<td>8.0</td>
<td>9.4 ± 0.92</td>
</tr>
<tr>
<td>COB-0</td>
<td>Granite</td>
<td>12.2</td>
<td>11.80</td>
<td>20.9</td>
<td>3.8 ± 0.39</td>
</tr>
<tr>
<td>MIF-00</td>
<td>Granite</td>
<td>0.7</td>
<td>0.86</td>
<td>1.5</td>
<td>4.8 ± 0.47</td>
</tr>
<tr>
<td>GRAN-O</td>
<td>Granite</td>
<td>9.6</td>
<td>22.10</td>
<td>39.0</td>
<td>9.1 ± 0.31</td>
</tr>
<tr>
<td>CHEL-O</td>
<td>Granite</td>
<td>8.5</td>
<td>18.00</td>
<td>34.0</td>
<td>7.8 ± 0.62</td>
</tr>
<tr>
<td>GRO-0</td>
<td>Granite</td>
<td>2.3</td>
<td>4.28</td>
<td>7.5</td>
<td>7.7 ± 0.39</td>
</tr>
<tr>
<td>PHM-100</td>
<td>Granite</td>
<td>2.0</td>
<td>4.29</td>
<td>7.5</td>
<td>7.7 ± 0.39</td>
</tr>
<tr>
<td>INS-0</td>
<td>Granite (N)</td>
<td>3.0</td>
<td>10.40</td>
<td>22.6</td>
<td>16.3 ± 0.26</td>
</tr>
<tr>
<td>VNK-274</td>
<td>Dacite</td>
<td>9.4</td>
<td>16.30</td>
<td>28.8</td>
<td>6.9 ± 0.81</td>
</tr>
<tr>
<td>E-823*</td>
<td>Symosite</td>
<td>5.3</td>
<td>12.40</td>
<td>21.9</td>
<td>9.3 ± 0.54</td>
</tr>
<tr>
<td>HIN-14</td>
<td>Lugasrite</td>
<td>14.7</td>
<td>57.20</td>
<td>99.0</td>
<td>15.4 ± 0.74</td>
</tr>
<tr>
<td>MBS-57</td>
<td>Basalt</td>
<td>0.4</td>
<td>0.20</td>
<td>0.5</td>
<td>2.8 ± 0.26</td>
</tr>
<tr>
<td>MBS-3</td>
<td>Basalt</td>
<td>1.3</td>
<td>0.64</td>
<td>1.5</td>
<td>3.8 ± 0.13</td>
</tr>
<tr>
<td>IFP-193</td>
<td>Diabase</td>
<td>2.3</td>
<td>4.52</td>
<td>7.9</td>
<td>7.7 ± 1.0</td>
</tr>
<tr>
<td>W-1*</td>
<td>Diabase</td>
<td>0.5</td>
<td>1.19</td>
<td>2.1</td>
<td>9.4 ± 1.6</td>
</tr>
<tr>
<td>I-374*</td>
<td>Gabbro</td>
<td>4.7</td>
<td>4.25</td>
<td>7.5</td>
<td>3.6 ± 0.50</td>
</tr>
<tr>
<td>AAS-256</td>
<td>Volc. tuff</td>
<td>55.0</td>
<td>23.2</td>
<td>41.0</td>
<td>1.7 ± 0.12</td>
</tr>
<tr>
<td>I-268*</td>
<td>Comaglomerate</td>
<td>4.6</td>
<td>2.71</td>
<td>4.8</td>
<td>2.3 ± 0.20</td>
</tr>
<tr>
<td>I-269*</td>
<td>Comaglomerate</td>
<td>9.0</td>
<td>23.40</td>
<td>41.2</td>
<td>10.4 ± 0.48</td>
</tr>
<tr>
<td>I-263*</td>
<td>Metacomasglerate</td>
<td>12.3</td>
<td>80.90</td>
<td>142.5</td>
<td>26.0 ± 0.91</td>
</tr>
<tr>
<td>SP-PR</td>
<td>Serpentinite</td>
<td>0.5</td>
<td>0.10</td>
<td>0.2</td>
<td>1.0 ± 0.63</td>
</tr>
<tr>
<td>I-372*</td>
<td>Quarzite</td>
<td>7.2</td>
<td>19.2</td>
<td>33.7</td>
<td>10.5 ± 0.86</td>
</tr>
<tr>
<td>OC-27</td>
<td>Quarzite</td>
<td>0.2</td>
<td>2.7</td>
<td>0.5</td>
<td>5.3 ± 0.49</td>
</tr>
<tr>
<td>OC-22</td>
<td>Quarzite</td>
<td>0.8</td>
<td>3.0</td>
<td>0.6</td>
<td>1.9 ± 0.19</td>
</tr>
<tr>
<td>OMK-PR</td>
<td>Sandstone</td>
<td>3.5</td>
<td>10.50</td>
<td>18.6</td>
<td>11.9 ± 0.94</td>
</tr>
<tr>
<td>AAC-218</td>
<td>Sandstone</td>
<td>5.1</td>
<td>4.18</td>
<td>7.3</td>
<td>3.2 ± 0.40</td>
</tr>
<tr>
<td>AAS-309</td>
<td>Sandstone</td>
<td>34.0</td>
<td>45.50</td>
<td>80.2</td>
<td>5.3 ± 0.22</td>
</tr>
<tr>
<td>AAF-374</td>
<td>Sandstone</td>
<td>3.4</td>
<td>6.40</td>
<td>11.2</td>
<td>7.4 ± 0.71</td>
</tr>
<tr>
<td>OMK-57</td>
<td>Red Silt</td>
<td>2.1</td>
<td>4.31</td>
<td>7.6</td>
<td>9.1 ± 1.02</td>
</tr>
<tr>
<td>E-825*</td>
<td>Dol. sarkose</td>
<td>8.3</td>
<td>43.20</td>
<td>20.7</td>
<td>5.6 ± 0.53</td>
</tr>
<tr>
<td>AUF-L</td>
<td>Limestone</td>
<td>1.9</td>
<td>0.68</td>
<td>1.3</td>
<td>1.6 ± 0.42</td>
</tr>
<tr>
<td>EL-AB-A</td>
<td>Arph./limestone</td>
<td>4.5</td>
<td>3.26</td>
<td>4.2</td>
<td>1.9 ± 0.27</td>
</tr>
<tr>
<td>EL-AB-O</td>
<td>col. limestone</td>
<td>2.6</td>
<td>0.40</td>
<td>0.7</td>
<td>0.6 ± 0.17</td>
</tr>
<tr>
<td>ESP-2L</td>
<td>Limestone</td>
<td>1.7</td>
<td>0.76</td>
<td>1.3</td>
<td>1.7 ± 0.56</td>
</tr>
<tr>
<td>EL-DOC-L</td>
<td>Limestone</td>
<td>5.5</td>
<td>3.11</td>
<td>5.5</td>
<td>2.2 ± 0.31</td>
</tr>
<tr>
<td>GC-5</td>
<td>Silt shale</td>
<td>3.2</td>
<td>62.3</td>
<td>10.9</td>
<td>7.7 ± 0.41</td>
</tr>
<tr>
<td>GC-3</td>
<td>Slate</td>
<td>1.7</td>
<td>8.10</td>
<td>14.2</td>
<td>2.67 ± 0.18</td>
</tr>
<tr>
<td>SP-5</td>
<td>Laterite (P)</td>
<td>14.2</td>
<td>17.5</td>
<td>30.8</td>
<td>3.86 ± 0.18</td>
</tr>
<tr>
<td>NPL-2</td>
<td>Laterite</td>
<td>0.9</td>
<td>5.7</td>
<td>9.9</td>
<td>5.26 ± 0.15</td>
</tr>
<tr>
<td>LIP-60</td>
<td>Volc.glass</td>
<td>9.5</td>
<td>1.3</td>
<td>2.1</td>
<td>0.51 ± 0.06</td>
</tr>
</tbody>
</table>

All samples were crushed and sieved to <60 >115 mesh unless indicated.
* = grain sizes < 200 mesh.
# = RNS rock standard
W = Weathered
TABLE II. RADON EMANATION CHARACTERISTICS – MINERALS

<table>
<thead>
<tr>
<th>MINERAL</th>
<th>cU (ppm)</th>
<th>$^{222}$Rn ACTIVITY (pCi/h·g)</th>
<th>EMANATION RATE (at. Rn/h·g)</th>
<th>ESCAPE-TO-PRODUCTION RATE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zircon (20)</td>
<td>416-2660</td>
<td>0.4-30 x10^{-2}</td>
<td>140-5220</td>
<td>0.2-4.8</td>
</tr>
<tr>
<td>Zircon (W)</td>
<td>405</td>
<td>1.2 x10^{-1}</td>
<td>2180</td>
<td>12.1</td>
</tr>
<tr>
<td>Sphene (15)</td>
<td>29-100</td>
<td>0.8-68 x10^{-4}</td>
<td>4-742</td>
<td>0.2-4.7</td>
</tr>
<tr>
<td>Biotite (2)</td>
<td>3-11</td>
<td>0.2-1.9 x10^{-3}</td>
<td>36-33</td>
<td>2.8-6.6</td>
</tr>
<tr>
<td>Monazite (1)</td>
<td>429</td>
<td>2.3 x10^{-3}</td>
<td>39</td>
<td>0.2</td>
</tr>
<tr>
<td>Xenotime (1)</td>
<td>6026</td>
<td>1.5 x10^{-2}</td>
<td>260</td>
<td>0.09</td>
</tr>
<tr>
<td>Apatite (1)</td>
<td>17</td>
<td>3.5 x10^{-4}</td>
<td>6</td>
<td>0.8</td>
</tr>
<tr>
<td>Allanite (1)</td>
<td>40.0</td>
<td>3.3 x10^{-4}</td>
<td>5.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Magnetite (Ti)</td>
<td>0.8</td>
<td>8.3 x10^{-5}</td>
<td>1.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Glaucnite (2)</td>
<td>1-22</td>
<td>1-18 x10^{-4}</td>
<td>1-39</td>
<td>3.0</td>
</tr>
</tbody>
</table>

a Figure in brackets is the number of samples analyzed.  
b W = weathered.

3. RESULTS

The physical characteristics of the $^{222}$Ra emanation for different types of rocks and accessory minerals are summarized in Tables I and II and shown graphically in Figs 2-4. In general, rocks are poor emanators, with the exception of the granitic types which sometimes show an escape-to-production rate of more than 10%. Weathering is an important factor in increasing the emanation (samples E-827, INK-G in Table I and zircon (W) in Table II). Materials like basalts, gabbros, ortho-quartzites and limestones (Fig. 2) are among the lowest emanators. Figure 3 suggests that the activity of the radon released from sedimentary rocks ranges widely and, if combined, will exceed by far the total radon release of igneous rocks into the atmosphere.

Table II shows the emanation characteristics of some common accessory minerals. Their uranium concentrations and the radon escape rates differ by two to three orders of magnitude. It is important, however, to note that their percentage of radon escape is very small both in value and range (Fig. 4). These results clearly show that the percentage of radon which escapes from a mineral is not correlated at all with the uranium concentration. Thus, xenotime and monazite with 6000 ppm and 400 ppm uranium, respectively, show smaller radon escape than biotite, apatite or sphene with 11 ppm, 17 ppm and 84 ppm uranium, respectively.

From a purely statistical standpoint, it would be desirable to have additional analyses for each type of sample. On the other hand, the time required to perform each analysis (3 d for uranium determination and
### Table III. Effect of Temperature on Radon Release from Rocks \(^a\)

<table>
<thead>
<tr>
<th>TEMPERATURE (^\circ\mathrm{C})</th>
<th>ACTIVITY (\text{pCi/\text{h} \cdot \text{g}})</th>
<th>RADON ESCAPE (\text{atoms/\text{h} \cdot \text{g}})</th>
<th>ESCAPE-TO-PRODUCTION RATE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 265</td>
<td>0.258x10(^{-2})</td>
<td>45</td>
<td>10.62 ± 0.30</td>
</tr>
<tr>
<td>+ 160</td>
<td>0.247x10(^{-2})</td>
<td>43</td>
<td>10.19 ± 0.41</td>
</tr>
<tr>
<td>+ 22</td>
<td>0.223x10(^{-2})</td>
<td>39</td>
<td>9.39 ± 0.30</td>
</tr>
<tr>
<td>- 20</td>
<td>0.197x10(^{-2})</td>
<td>35</td>
<td>8.14 ± 0.32</td>
</tr>
<tr>
<td>- 80</td>
<td>0.682x10(^{-3})</td>
<td>12</td>
<td>2.81 ± 0.18</td>
</tr>
</tbody>
</table>

\(^a\) Graniteville granite

![Graph showing temperature dependence of radon escape](image)

**FIG. 5.** Temperature dependence of radon escape.

15-20 d for radon de-emanation and counting), as well as the availability of suitable samples, place severe restrictions on the number of analyses that can be made.

### 3.1. Temperature dependence of radon emanation

The influence of temperature on the emanation rate was investigated for the range -80°C to +265°C, using the NBS rock standard Graniteville granite. The radium concentration is given by NBS as \(3.3 \times 10^{12}\) g per gram of rock.
(9.6 ppm uranium equivalent) and the grain sizes as -60 to +100 mesh. Sample weights of 5 g were used. The temperatures of the investigation were kept constant during the entire period of de-emanation (radon accumulation). The results are given in Table III and Fig. 5. A very slight increase in the percentage of radon escape was observed for de-emanation at temperatures above 25°C; however, the low temperatures drastically reduce the radon release, i.e. there is a decrease of 13.5% at -20°C and of 70% at -80°C.

3.2. Diffusion of radon through solid rock

The distance through which radon can be mobilized and brought to the surface characterizes the different types of rocks. Guedalia et al. [25] studied the effects of soil thickness on the emanation of $^{220}$Rn (the $^{232}$Th-series radon, half-life = 55 s) by adding successive layers of identical soil. They observed an increase in the emanation up to 6-7 cm of soil thickness. They also observed that the emanation from the first 2 cm contributes to 75% of the total emanation rate.

Taking these values and assuming that the diffusion properties of $^{220}$Rn are identical to those of $^{222}$Rn, it is possible to calculate, theoretically, the corresponding depth for $^{222}$Rn mobilization, multiplying by the difference in half-lives:

$^{220}$Rn \[ 55 \text{ s} \quad 6-7 \text{ cm} \]
$^{222}$Rn \[ 3.825 \text{ d} \quad 360-420 \text{ m} \]

This theoretical depth of 350-400 m for $^{222}$Rn seems unrealistically large, inasmuch as natural conditions (e.g. porosity, layering, packing, humidity and density) do not remain homogeneous over such a vertical distance which considerably reduces these depths. It seems reasonable to hypothesize that, for certain rock formations, $^{222}$Rn can reach the surface before decay begins from a depth of at least 30-40 m. It is interesting to note that, according to recent reports from General Electric, their track etch technique developed for uranium exploration was able to detect radon anomalies over workable uranium ore at depths of 300 to 400 ft of sedimentary rock.

Fresh solid rock, because of its low permeability and type of uranium distribution (mostly in accessory minerals), is expected to have a much shorter range for $^{222}$Rn diffusion.

To study this depth of mobilization on granitic rocks, an experiment was devised utilizing rock cores encapsulated in plastic epoxy (styrene) in such a way as to have a 1-cm-thick coating of plastic. The base of the plastic cylinder was cut to expose one end of the core. Then 5 g of 1% uranium powder (escape-to-production rate of 9.4%) inside a thick plastic container was hermetically sealed with epoxy on to the clean base of the core. The plastic covering the upper part of the core was cut off, exposing the surface of the core at a length of 15 cm. In the first analysis it was verified that approximately 85% of the total radon produced by the uranium powder in the core base was escaping through the top surface. The possibility that radon was travelling along the core-plastic interface was considered, and other experiments were developed to test this hypothesis. These experiments indicated, however, that diffusion along the wall was unlikely and that the radon produced by the uranium powder at the base of the core diffuses through 15 cm of solid granite before decay.
Although these experimental observations indicate rapid diffusion of radon through such substantial thicknesses of solid fresh granite, it is difficult to understand the mechanism, especially considering the accepted low permeability of granite and the absence of any pressure gradient for this experiment. Previous reports of this phenomenon were not found in the literature. Because of the lack of independent data which would or would not support the above laboratory observations, the interpretations or derived consequences will not be discussed further.

3.3. Total alpha dose and emanation

The natural radiation damage which may be present in a crystal is directly proportional to the total alpha dose received by the sample. Thus the uranium and thorium concentrations present in each sample must be determined with accuracy.

Both the uranium and thorium concentrations in the eight zircon samples shown in Table IV and the uranium concentrations in all other 27 samples given in Tables V-VII were determined by thermal ionization procedures on a mass spectrometer; the uncertainty is about 1%. For the Minnesota-Ontario sphenes and the samples from Finland the thorium concentrations were determined at Rice University by means of gamma-ray spectrometric analyses. Because of the small sample weight and low concentrations of uranium and thorium (especially in the sphenes), the sample activity to background ratios are not favourable; thus relatively large errors may be expected in the thorium determination. However, as the activity of the thorium alone corresponds to 10-20% of the total activity, the calculated dose will be relatively unaffected by the larger uncertainty in the thorium determination.

Tables VIII to XI show the natural radiation activities and dosages received by the samples, calculated with the equation given by Holland and Gottfried [26] for the total alpha disintegration per milligram.

In Table VIII it may be observed that the activities are practically the same for all the zircons with the exception of sample HWDT, which has a high uranium and thorium content. Sample 373 is weathered and has 55% apparent lead loss, with the actual loss being greater if uranium was leached out as suggested by the average uranium content of fresh zircons in the same rock (Stern et al. [27]). Then, assuming a pre-weathered and leached uranium concentration equal to twice the present value, the second values for this sample were obtained.

In the case of samples C-2, C-3, CAA-15, CAA-17 and WSE-13, approximately the same relatively low dosage was found, about $1 - 5 \times 10^{15}$ a/mg and a correspondingly low percentage of radon loss. Sample HWDT was subjected to a higher dose and presents a higher radon escape. Sample 373 consists of recently weathered zircon (Stern et al. [27]), and this weathering could leach out a significant fraction of $^{226}$Ra and other intermediate daughters. If this is not taken into account, the emanation rate is underestimated because the assumed secular equilibrium does not really exist. However, a compensating effect is at work. The weathering may increase the permeability of the material for direct radon diffusion, thereby raising the present percentage of radon escape above that applicable to most of the sample history. This probably explains the anomalously high radon escape of 12% for the sample.
TABLE IV. RADON EMANATION CHARACTERISTICS
Zircon samples

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>WEIGHT (g)</th>
<th>CONCENTRATIONS (ppm)</th>
<th>ACTIVITY (dis/h)</th>
<th>EMANATION RATE (at. Rn/h·g)</th>
<th>ESCAPE-TO-PRODUCTION RATE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>238 U</td>
<td>232 Th</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-2</td>
<td>1.054</td>
<td>570.1</td>
<td>284.2</td>
<td>$2.69 \times 10^4$</td>
<td>$2.08 \times 10^2$</td>
</tr>
<tr>
<td>C-3</td>
<td>0.866</td>
<td>867.6</td>
<td>404.2</td>
<td>$3.38 \times 10^4$</td>
<td>$0.65 \times 10^2$</td>
</tr>
<tr>
<td>HWDT b</td>
<td>1.482</td>
<td>2660</td>
<td>1549</td>
<td>$1.75 \times 10^5$</td>
<td>$5.51 \times 10^3$</td>
</tr>
<tr>
<td>C&amp;A-15</td>
<td>0.511</td>
<td>757.6</td>
<td>373.9</td>
<td>$1.72 \times 10^4$</td>
<td>$3.16 \times 10^2$</td>
</tr>
<tr>
<td>C&amp;A-17</td>
<td>0.796</td>
<td>504.7</td>
<td>180.9</td>
<td>$1.78 \times 10^4$</td>
<td>$3.42 \times 10^2$</td>
</tr>
<tr>
<td>373</td>
<td>0.735</td>
<td>405.8</td>
<td>127.5</td>
<td>$1.32 \times 10^4$</td>
<td>$2.21 \times 10^3$</td>
</tr>
<tr>
<td>WSE-13</td>
<td>1.274</td>
<td>416.4</td>
<td>154.2</td>
<td>$2.36 \times 10^4$</td>
<td>$1.40 \times 10^2$</td>
</tr>
<tr>
<td>346</td>
<td>0.043</td>
<td>601.9</td>
<td>159.1</td>
<td>$1.15 \times 10^3$</td>
<td>$0.84 \times 10^2$</td>
</tr>
</tbody>
</table>

a Figure in brackets is the average number of analyses.
b Unleached.

TABLE V. RADON EMANATION CHARACTERISTICS
Zircon samples from Finland

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>WEIGHT (g)</th>
<th>CONCENTRATIONS (ppm)</th>
<th>ACTIVITY (dis/h)</th>
<th>EMANATION RATE (at. Rn/h·g)</th>
<th>ESCAPE-TO-PRODUCTION RATE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>238 U</td>
<td>232 Th</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-6b</td>
<td>0.705</td>
<td>711.0</td>
<td>645</td>
<td>$2.21 \times 10^4$</td>
<td>485</td>
</tr>
<tr>
<td>A-24</td>
<td>0.130</td>
<td>848.7</td>
<td>132</td>
<td>$4.87 \times 10^3$</td>
<td>517</td>
</tr>
<tr>
<td>A-25</td>
<td>0.574</td>
<td>1123.8</td>
<td>141</td>
<td>$2.80 \times 10^4$</td>
<td>1025</td>
</tr>
<tr>
<td>A-73</td>
<td>0.922</td>
<td>657.3</td>
<td>243</td>
<td>$2.67 \times 10^4$</td>
<td>631</td>
</tr>
<tr>
<td>A-169</td>
<td>0.757</td>
<td>1053.3</td>
<td>445</td>
<td>$3.52 \times 10^4$</td>
<td>2220</td>
</tr>
<tr>
<td>A-176</td>
<td>0.283</td>
<td>1174.4</td>
<td>549</td>
<td>$1.46 \times 10^4$</td>
<td>2310</td>
</tr>
<tr>
<td>A-229</td>
<td>0.363</td>
<td>415.2</td>
<td>177</td>
<td>$6.60 \times 10^3$</td>
<td>282</td>
</tr>
<tr>
<td>A-240</td>
<td>0.279</td>
<td>313.5</td>
<td>187</td>
<td>$3.83 \times 10^3$</td>
<td>23</td>
</tr>
<tr>
<td>A-255</td>
<td>0.388</td>
<td>122.0</td>
<td>102</td>
<td>$2.09 \times 10^3$</td>
<td>45</td>
</tr>
<tr>
<td>A-334</td>
<td>0.219</td>
<td>216.7</td>
<td>271</td>
<td>$1.97 \times 10^3$</td>
<td>65</td>
</tr>
<tr>
<td>A-335</td>
<td>0.646</td>
<td>428.6</td>
<td>178</td>
<td>$1.22 \times 10^4$</td>
<td>244</td>
</tr>
<tr>
<td>A-362</td>
<td>1.040</td>
<td>552.2</td>
<td>190</td>
<td>$2.53 \times 10^4$</td>
<td>235</td>
</tr>
</tbody>
</table>
### TABLE VI. RADON EMANATION CHARACTERISTICS
Sphenes from northeast Minnesota and northwest Ontario

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>WEIGHT (g)</th>
<th>CONCENTRATIONS (ppm)</th>
<th>ACTIVITY $\times 10^3$ (dis/h)</th>
<th>EMANATION RATE (at. Rn/h·g)</th>
<th>ESCAPE-TO-PRODUCTION RATE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL-16</td>
<td>1.236</td>
<td>41.0</td>
<td>2.25</td>
<td>3.5</td>
<td>0.17 ± 0.04 (4)²</td>
</tr>
<tr>
<td>SS-4</td>
<td>0.680</td>
<td>42.7</td>
<td>1.11</td>
<td>27.5</td>
<td>1.45 ± 0.12 (3)</td>
</tr>
<tr>
<td>MN-11</td>
<td>2.235</td>
<td>29.7</td>
<td>2.95</td>
<td>20.4</td>
<td>1.50 ± 0.08 (2)</td>
</tr>
<tr>
<td>DKL-2B</td>
<td>1.364</td>
<td>100.8</td>
<td>6.11</td>
<td>118.0</td>
<td>2.62 ± 0.20 (2)</td>
</tr>
<tr>
<td>M-5218</td>
<td>1.227</td>
<td>61.6</td>
<td>3.36</td>
<td>35.8</td>
<td>1.29 ± 0.08 (3)</td>
</tr>
<tr>
<td>M-5219</td>
<td>1.999</td>
<td>17.0</td>
<td>1.51</td>
<td>0.7</td>
<td>0.10 ± 0.04 (2)</td>
</tr>
<tr>
<td>M-5220</td>
<td>0.193</td>
<td>45.1</td>
<td>3.87</td>
<td>14.2</td>
<td>0.68 ± 0.25 (3)</td>
</tr>
<tr>
<td>MN-41-70</td>
<td>0.368</td>
<td>37.5</td>
<td>6.14</td>
<td>1.4</td>
<td>0.09 ± 0.03 (2)</td>
</tr>
</tbody>
</table>

Table VI displays twelve zircon concentrates from Finland. These samples, collected in different areas and from different rock types, very clearly show a trend by which those which received high alpha doses indicate a larger percentage of radon loss. The zircons A-176, A-169, A-25 and A-73 received the highest doses and, as a direct systematic consequence, display higher and higher radon losses. Sample A-416 in Table XI received a high alpha dose and its emanation rate corresponds to that of other high emanators (Table VI). Samples A-168 and A-169 in Table XI, which apparently also received high alpha doses, show a relatively small radon loss. The interpretation of these results must be done carefully, taking into account the geological history of the samples.

### TABLE VII. RADON EMANATION CHARACTERISTICS
Sphenes from Finland

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>WEIGHT (g)</th>
<th>CONCENTRATIONS (ppm)</th>
<th>ACTIVITY $\times 10^3$ (dis/h)</th>
<th>EMANATION RATE (at. Rn/h·g)</th>
<th>ESCAPE-TO-PRODUCTION RATE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-168</td>
<td>0.334</td>
<td>141.8</td>
<td>2.10 $\times 10^3$</td>
<td>110</td>
<td>1.25±0.16 (9)²</td>
</tr>
<tr>
<td>A-169</td>
<td>0.388</td>
<td>152.7</td>
<td>2.63 $\times 10^3$</td>
<td>29</td>
<td>0.43±0.16 (2)</td>
</tr>
<tr>
<td>A-334</td>
<td>0.313</td>
<td>104.6</td>
<td>1.45 $\times 10^3$</td>
<td>114</td>
<td>2.35±0.19 (2)</td>
</tr>
<tr>
<td>A-357</td>
<td>0.080</td>
<td>80.0</td>
<td>2.86 $\times 10^2$</td>
<td>150</td>
<td>4.00±0.45 (2)</td>
</tr>
<tr>
<td>A-397</td>
<td>0.838</td>
<td>30.0</td>
<td>1.11 $\times 10^3$</td>
<td>3</td>
<td>0.21±0.08 (3)</td>
</tr>
<tr>
<td>A-416</td>
<td>0.232</td>
<td>77.8</td>
<td>8.02 $\times 10^2$</td>
<td>165</td>
<td>4.40±0.32 (2)</td>
</tr>
<tr>
<td>A-429</td>
<td>0.292</td>
<td>207²</td>
<td>1.77 $\times 10^3$</td>
<td>742</td>
<td>8.06±0.39 (2)</td>
</tr>
</tbody>
</table>

Table VII displays twelve zircon concentrates from Finland. These samples, collected in different areas and from different rock types, very clearly show a trend by which those which received high alpha doses indicate a larger percentage of radon loss. The zircons A-176, A-169, A-25 and A-73 received the highest doses and, as a direct systematic consequence, display higher and higher radon losses. Sample A-416 in Table XI received a high alpha dose and its emanation rate corresponds to that of other high emanators (Table VI). Samples A-168 and A-169 in Table XI, which apparently also received high alpha doses, show a relatively small radon loss. The interpretation of these results must be done carefully, taking into account the geological history of the samples.
TABLE VIII. NATURAL RADIATION DOSAGES
Zircon samples

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>AGES IN MILLION YEARS</th>
<th>PRESENT ALPHA ACTIVITY ((10^6) a/mg)</th>
<th>TOTAL ALPHA/mg SINCE FORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(206_{\text{pb}}/238_{\text{U}})</td>
<td>(207_{\text{pb}}/206_{\text{pb}})</td>
<td></td>
</tr>
<tr>
<td>C-2</td>
<td>1310 ± 25</td>
<td>1444 ± 15</td>
<td>2.04 (\times 10^6)</td>
</tr>
<tr>
<td>C-3</td>
<td>1340 ± 25</td>
<td>1416 ± 15</td>
<td>3.13 (\times 10^6)</td>
</tr>
<tr>
<td>HWDT</td>
<td>573 ± 10</td>
<td>1338 ± 15</td>
<td>9.70 (\times 10^6)</td>
</tr>
<tr>
<td>CAA-15</td>
<td>1280 (a)</td>
<td>1456</td>
<td>2.72 (\times 10^6)</td>
</tr>
<tr>
<td>CAA-17</td>
<td>1022 (a)</td>
<td>1640</td>
<td>1.76 (\times 10^6)</td>
</tr>
<tr>
<td>373</td>
<td>1575 (a)</td>
<td>3380</td>
<td>1.40 (\times 10^6)</td>
</tr>
<tr>
<td>WSE-13</td>
<td>710</td>
<td>804</td>
<td>1.45 (\times 10^6)</td>
</tr>
<tr>
<td>346</td>
<td>2570</td>
<td>2640</td>
<td>2.05 (\times 10^6)</td>
</tr>
</tbody>
</table>

\(a\) Errors not available.

\(b\) Calculated assuming a pre-weathered U-Th concentration equal to twice the presently measured value.

TABLE IX. NATURAL RADIATION DOSAGES
Zircon samples from Finland

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>AGES IN MILLION YEARS</th>
<th>PRESENT ALPHA ACTIVITY ((10^6) a/mg)</th>
<th>TOTAL ALPHA/mg SINCE FORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(206_{\text{pb}}/238_{\text{U}})</td>
<td>(207_{\text{pb}}/206_{\text{pb}})</td>
<td></td>
</tr>
<tr>
<td>A-6b</td>
<td>1600</td>
<td>2150</td>
<td>2.80</td>
</tr>
<tr>
<td>A-24</td>
<td>1550</td>
<td>1900</td>
<td>3.03</td>
</tr>
<tr>
<td>A-25</td>
<td>1250</td>
<td>1900</td>
<td>3.79</td>
</tr>
<tr>
<td>A-73</td>
<td>2050</td>
<td>2740</td>
<td>2.33</td>
</tr>
<tr>
<td>A-169</td>
<td>860</td>
<td>1800</td>
<td>3.83</td>
</tr>
<tr>
<td>A-176</td>
<td>670</td>
<td>2150</td>
<td>4.25</td>
</tr>
<tr>
<td>A-229</td>
<td>1630</td>
<td>1900</td>
<td>1.43</td>
</tr>
<tr>
<td>A-240</td>
<td>1870</td>
<td>1915</td>
<td>1.10</td>
</tr>
<tr>
<td>A-255</td>
<td>1520</td>
<td>1700</td>
<td>0.50</td>
</tr>
<tr>
<td>A-334</td>
<td>1650</td>
<td>1850</td>
<td>0.83</td>
</tr>
<tr>
<td>A-335</td>
<td>1380</td>
<td>1850</td>
<td>1.52</td>
</tr>
<tr>
<td>A-362</td>
<td>2120</td>
<td>2400</td>
<td>1.95</td>
</tr>
</tbody>
</table>
### TABLE X. NATURAL RADIATION DOSAGES
Sphenes from northeast Minnesota and northwest Ontario

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>AGES IN MILLION YEARS</th>
<th>PRESENT ALPHA ACTIVITY (10^9 a/mg a)</th>
<th>TOTAL ALPHA/mg SINCE FORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>206 Pb/238 U (1)</td>
<td>207 Pb/206 Pb (2)</td>
<td></td>
</tr>
<tr>
<td>NB-16</td>
<td>2730</td>
<td>2700</td>
<td>1.81</td>
</tr>
<tr>
<td>SS-4</td>
<td>2710</td>
<td>2750</td>
<td>2.48</td>
</tr>
<tr>
<td>MN-11</td>
<td>2510</td>
<td>2740</td>
<td>1.72</td>
</tr>
<tr>
<td>DKL-28</td>
<td>1910</td>
<td>2740</td>
<td>3.88</td>
</tr>
<tr>
<td>M-5215a</td>
<td>2710</td>
<td>(7.25) b</td>
<td>2680</td>
</tr>
<tr>
<td>M-5219a</td>
<td>2595</td>
<td>(3.31)</td>
<td>2690</td>
</tr>
<tr>
<td>M-5220a</td>
<td>2510</td>
<td>(1.70)</td>
<td>2555</td>
</tr>
<tr>
<td>MN-41-70a</td>
<td>2050</td>
<td>(0.5)</td>
<td>2520</td>
</tr>
</tbody>
</table>

a Samples in the zone of metamorphic contact, with emanation characteristics affected by temperature.
b Distance from the contact (in km).

### TABLE XI. NATURAL RADIATION DOSAGES
Sphenes from Finland

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>AGES IN MILLION YEARS</th>
<th>PRESENT ALPHA ACTIVITY (10^9 a/mg a)</th>
<th>TOTAL ALPHA/mg SINCE FORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>206 Pb/238 U (1)</td>
<td>207 Pb/206 Pb (2)</td>
<td></td>
</tr>
<tr>
<td>A-168</td>
<td>1770</td>
<td>1800</td>
<td>5.40</td>
</tr>
<tr>
<td>A-169</td>
<td>1780</td>
<td>1800</td>
<td>6.00</td>
</tr>
<tr>
<td>A-334</td>
<td>1670</td>
<td>1780</td>
<td>4.43</td>
</tr>
<tr>
<td>A-357</td>
<td>1780</td>
<td>1980a</td>
<td>5.83</td>
</tr>
<tr>
<td>A-397</td>
<td>1740</td>
<td>1750</td>
<td>1.45</td>
</tr>
<tr>
<td>A-416</td>
<td>1700</td>
<td>2200</td>
<td>3.55</td>
</tr>
</tbody>
</table>

a Age of metamorphism.

Some of the old Pre-Karelian zircons are little affected by the later Svecokarelian orogeny of 1900 million years ago, as their 206Pb/207Pb ages are lower than the estimated 2800 million years for these basement rocks. However, the co-genetic sphenes had their age record erased (see, for example, sphene A-357 in Table XI), and their present lead-lead ages date the metamorphic event.

The first four Minnesota-Ontario sphenes listed in Table X have 206Pb/207Pb ages of 2680-2750 million years, and an isochron of 2730 million years is used by Catanzaro and Hanson [28]. Although a low-grade metamorphism (prehnite-pumpellyite facies) is reported to have occurred in the area 1600 million years ago, the dosages were estimated as if this thermal event had no influence.
FIG. 6. Variation of radon loss with temperature — granite.

FIG. 7. Variation of radon loss with temperature — zircon crystal.
ZIRCON SAND
\( \text{ZrSiO}_4 \)
Origin: Zr Sand Beach Deposit, Australia

<table>
<thead>
<tr>
<th>eU (ppm)</th>
<th>eTh (ppm)</th>
<th>Observed Radon Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>260</td>
<td>320</td>
<td></td>
</tr>
</tbody>
</table>

RT 0.174%
400°C 0.155%
600°C 0.099%
800°C 0.056%
1000°C 0.016%
1200°C 0.016%

FIG. 8. Variation of radon loss with temperature — zircon sand.

SPHENE
\( \text{CaTiO(SiO}_4 \)
Origin: Pegmatite De Kalb, N.Y.

<table>
<thead>
<tr>
<th>eU (ppm)</th>
<th>eTh (ppm)</th>
<th>Observed Radon Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>84</td>
<td>91</td>
<td></td>
</tr>
</tbody>
</table>

RT 0.61%
200°C 0.57%
400°C 0.39%
600°C 0.17%
800°C 0.13%
1000°C 0.10%
1200°C 0.10%

FIG. 9. Variation of radon loss with temperature — sphene.
FIG. 10. Variation of radon loss with temperature — xenotime.

FIG. 11. Variation of radon loss with temperature — monazite.
4. TEMPERATURE-ANNEALING EFFECTS ON RADON ESCAPE

The hypothesis that radiation damage of minerals is related to radon diffusion was tested by analysing samples of granite, zircon crystal, zircon sand, sphene, xenotime, and monazite. The objective was to anneal progressively the natural radiation and mechanical damage present in the crystal structure and, by performing a $^{222}\text{Rn}$ analysis after each temperature stage, to determine whether any relationship exists between annealing and radon escape. All samples were analysed initially at room temperature, then stepwise heated for 24-h periods in 200°C increments. The results are displayed in Figs 6-11, where the percentage of radon escape is normalized to 1.0 at room temperature.

An overall decrease of radon escape on the order of 80-90% for temperatures above 1000°C is seen for all the samples except for xenotime and monazite. Above 800-1000°C the curves tend to parallel the abscissa as almost no radon leaks out of the grain interiors. The percentage of radon loss observed after these high-temperature treatments is probably only that from diffusion through the grain surfaces plus that from superficial impurities not removed by the ultrasonic cleaning.

The xenotime and monazite samples exhibit a slightly different behaviour, with the radon escape being less reduced within the final range of the temperature treatment. As both mineral concentrates contained zircon impurities, the observed effect may be a composite of the properties of the two minerals. Figures 10 and 11 show that the radon escape rate from these minerals is little affected within the range of 100-200°C. From 300-700°C the curves are characterized by similar slopes, being only offset along the temperature axis. Xenotime seems to be the least sensitive to temperature treatment. The only different slope observed was that for monazite. This slope is less steep, and a wider spread of results was obtained for the 200°C steps for the two samples analysed.

The temperature effect on the emanation rate of radon seems to be related to the stability of the crystal structure once damaged. The curves suggest that, whatever the phenomenon is, it is a continuous process but with variable rates. As only heat treatment was involved, the decrease in radon escape is presently attributed to the progressive annealing of the existing crystal damages.

This concept of the process agrees with the range of temperatures for fission-track annealing in zircon (Fleischer et al. [29]). However, it would appear that in order to completely anneal the natural radiation damage in zircon (restoring the crystallinity), to prevent radon diffusion from the internal sites, we must go either to higher temperatures or longer times than those indicated by fission-track annealing experiments. The work of Vaz and Senftle [30] on thermoluminescence of radiation-damaged zircon supports this hypothesis in that they found it necessary to heat zircon for approximately 20 h at 950°C to restore the thermoluminescence.

To investigate the dependence of emanation on natural radiation damage produced solely by uranium fission tracks, the granite, zircon crystals, and zircon sand, after their final temperature treatment (and thus substantial annealing) were irradiated in a flux of thermal neutrons to a dose of $10^{16}$ n·cm$^{-2}$.

These irradiated samples were de-emanated once again using the same procedure as before. The results were identical to the low values found
before neutron irradiation. This finding seems to indicate that uranium fission tracks alone are not sufficient to establish a network of damage extreme enough to influence the radon escape. These experimental results are in agreement with Pellas' [31] conclusion from his study of metamictic zircons that alpha decay is the most important damaging factor.

5. CONCLUSIONS

The results presented here indicate that radon emanation occurs not only from the porous media of soils and ordinary rocks but there is also a significant diffusion of radon from the production sites within crystal structures to the grain surfaces. Rocks show a wide range of radon loss with values ranging from 1 to 20% of the total radon produced under identical laboratory conditions. The granitic rocks are the major contributors among common rocks to radon release to the atmosphere, whereas basic and calcareous rocks are only minor contributors.

The activity of the radon released by sandstones, conglomerates and granites is larger than that from all other rock types together. Thus the best natural shielding materials to be used in the construction of low-level radiation facilities would be limestone, gabbro, and serpentinites, which besides their low uranium concentration have a small percentage of radon escape, in general less than 1%. Although a majority of rock-forming minerals contain traces of uranium and thorium, these elements are largely concentrated in accessory minerals. When fresh, these minerals (sphene, apatite, allanite, zircon, thorite) show very low radon emanation, i.e. less than 1%.

The lack of dependence of emanation on parent uranium concentrations was clearly established. Xenotime and monazite with high uranium concentrations have much smaller radon escape than apatite or biotite, both with much lower uranium concentrations. It thus appears that the emanation characteristics of crystals are related to the stability of their crystal structures.

Minerals whose atomic structure will retain the radiation damage effects, especially those reaching the metamictic state, will then be among the strongest radon emanators. Minerals with self-annealing properties, by contrast, will show a small percentage of radon loss. In this case the diffusion is mainly through the grain surface and mechanical defects, microfissures and dislocations.

The technique reported for sample preparation and radon transfer is simple and fast. Also, because no chemical treatment is involved and soil samples can be analysed as they are collected, the attractive feature of this technique is the very low price per analysis. Such low-level radiation detection systems can easily be modified to operate on batteries and be operated in a ground vehicle or field station. Thus, direct sampling of the upper soil porous media or de-emanation procedures as described will allow the detection of any mixture of uranium-bearing industrial products, such as tailings, in the regional soil background, road base and construction material.

The instrumental techniques developed in this research can be used as environment monitoring tools in the selection of adequate construction material to be used in schools and public buildings. It is especially attractive
in the case of low-level counting facilities, e.g. hospital whole-body counting rooms and low-level counting laboratories.

The de-emanation techniques used in this study also have direct application in the uranium exploration industry where most of the concentration or grade analysis is done by gamma-ray spectrometry using the $^{214}\text{Bi}$ 1.76-MeV photopeak. Paper IAEA-PL/565-8 in these Proceedings shows that ores present a still larger range of radon escape than common rocks, some very high, some relatively low. Also, it is common experience that not all uranium ores require sealing and waiting for the radon build-up and equilibrium with its daughters for an adequate grade determination. Thus the evaluation of the ore emanating characteristics will determine the need for sealing the material in containers prior to the spectrometric analysis, and above all, drill core analysis should provide some information for future mine ventilation plans.

ACKNOWLEDGEMENTS

The work was done at Rice University, Houston, Tex., and supported by the International Atomic Energy Agency (IAEA-NASA grant NGR-44-006-144) and the Department of Defense (contract No. DACA 39 69-C-0048). The zircon and sphene concentrates were obtained on loan from Drs. O. Kouvo from the Geological Survey of Finland, R.B. Doe and T.W. Stern from the U.S. Geological Survey and G.N. Hanson from the State University of New York at Story Brook. The powdered rock samples were obtained from Mr. P.H. Dodd from the U.S. Atomic Energy Commission at Grand Junction, Colorado. I am grateful for their assistance.

REFERENCES

DISCUSSION

S.R. AUSTIN: I don't think I have said very much on a problem that has puzzled many workers — does the radon traverse a distance of solid rock? One worker was interested in the rapid rate of radon escape through the damage zones in crystals. He came to the conclusion that this could not be represented by pure gaseous diffusion, as the rate of escape was too high, but that there must be some phenomenon such as the radon atom bouncing or ricocheting from wall to wall along the 'passage way'. I think that was pure speculation, but that is the best explanation I have seen in the literature.

P.M.C. BARRETTO: Indeed, the radon behaviour is interesting. For example, it is a common laboratory technique to date rocks by measuring the amount of argon gas produced within the minerals by the decay of $^{40}$K. It is called the K-Ar dating method. The argon, which is a noble gas and has not a short half-life as has the radon, practically does not escape from minerals. If it did escape the technique would not be useful. If you ask: "Why does the argon not escape while the radon does?" my answer would be: "I do not know". During this investigation I was led to believe that it was probably a question of production site, namely, the site where the $^{40}$Ar is produced within the mineral is far from and not related to the production site of $^{222}$Rn gas. Around the $^{40}$Ar production site there is not much radiation damage in the crystal lattice, whereas radon is produced very close to the $^{238}$U site, the surroundings of which are greatly damaged by the alpha disintegrations of the uranium series. Thus, the mineral structure is broken and the radon has a chance of bouncing and ricocheting around, as you say, degrading its 90-keV energy and moving away from its original production site. I do not know if this clarifies what you said, but I certainly agree that it is an intriguing point.

P. ZETTWOOG: What do you think would be the percentage of emanation in the case of obsidian?

P.M.C. BARRETTO: For this sample the emanation was very low, 0.5% if the 0.1 mm grain size class is considered. This low observed emanation also reflects the temperature problem. The temperature experiments indicate, I believe, that, once you remove all the crystal's existing damage, the observed residual emanation comes only from the crystal surface — produced as a result of a recoil atom, that is, there is apparently
no radon coming through the internal structure itself. Thus, according to the temperature curves shown, if the obsidian is a geologically recently cooled material, the emanation to be expected should be small.

P. ZETTWOOG: Nevertheless, I am surprised that, beyond a certain temperature, for example 1000°C, you have not observed degassing of the rock or diffusion of radon through the mass, which begins to become very fluid.

P. M. C. BARRETTO: I have not done temperature experiments with the volcanic glass, but only with zircon and sphene, which have high melting points, and xenotime and monazite, which stand 900°C without problems. Regarding the temperature range selected, I could only go to 1000°C because the furnace used was inadequate for higher temperatures. Also, I had information\(^1\) that, to restore thermoluminescence (crystallinity) in zircons, it was necessary to heat the crystals for approximately 20 hours at 950°C.

Now, regarding degassing or diffusion, the radon measurements were not made simultaneously with the temperature treatment, but always afterwards. The degassing would occur, presumably, only during the heating periods, and thus could not be observed.

C. PALMITER: In section 3.3 of your text you discuss alpha doses and show which samples received high alpha doses. I am confused about the units that you are using and the terminology of alpha doses. In Table X, I believe, you have \(10^{15}\) alphas per milligram per year. Are these radiation doses that you are talking about or are they integration rates?

P. M. C. BARRETTO: The expression 'alpha dose' as employed in the paper means the integration of all alphas produced within the mineral from the decay of its uranium and thorium concentration. The alpha dose is estimated from the radioactive concentration, the age and the sample weight. Knowing these parameters it is possible to estimate, approximately, the number of alpha disintegrations per milligram that the material was subjected to.

W. GRAY: Were the measurements made by cooling the sample down to room temperature or were they done at high temperature?

P. M. C. BARRETTO: The samples were put into the furnace and heated for 24 hours in a platinum crucible, for example at 400°C; they were then removed from the furnace, cooled to room temperature, again sealed into a flask and stored for 20 days before the gas was transferred to the alpha counting chamber. This procedure was repeated at every temperature step.

F. E. McGINLEY (Chairman): Maybe some of the confusion that has arisen in regard to Mr. Palmiter's question has to do with the conflict that exists between what he thinks of as dose and what you are using in your presentation. When you use the expression dose in your paper are you thinking of the alpha radiation that the crystal has received through geologic time or through the time of existence of that crystal?

P. M. C. BARRETTO: The alpha dose I refer to is caused by the decay of the naturally occurring uranium and thorium in that particular crystal during its assumed existence time or age. It is not an external dose coming from the surrounding rock material but only from the 'internal' radioactivity.

J. CAMERON: Is there any thought on doing similar work on the normal uranium ore-bearing minerals?

---

P.M.C. BARRETTO: I believe the next paper will give us excellent information on this subject as well as the practical applications. In the work described in my paper, the objective was to investigate the mechanisms of radon escape. To simplify the problems that may influence the radon escape of a mineral assembly found in a rock or an ore, avoiding several physical parameters such as porosity, humidity and grain size, I decided to work with single mineral phases like zircon, sphene, monazite, etc.

With regard to the diffusion of radon through solid materials, I would like to add a few further comments: Working with 2 mm thick polyethylene tubes, in which uranium ore was sealed, I observed that a substantial amount of the radon produced inside the tube escaped through the polyethylene wall. Also, it is interesting to recall that there are reports of concentrations of radon in the atmosphere of underground low-level radioactivity counting facilities that are higher than the concentration in the atmospheric air outside. Such is the case of the place where I worked, despite the fact that we had thick walls of low-activity concrete made with sea shells, one of the natural materials with the lowest uranium and thorium concentrations.
A LABORATORY STUDY OF RADON EMANATION FROM DOMESTIC URANIUM ORES

S.R. AUSTIN
Denver Mining Research Center,
United States Bureau of Mines,
Denver, Colo.,
United States of America

Abstract

Laboratory measurements of radon emanation were made by a slightly modified sealed-can gamma-only method of radiometric assaying for equivalent uranium. When a sample is sealed in a container, the percentage build-up of gamma activity of the radon daughters, lead-214 and bismuth-214, from sealing time to equilibrium is equal to the percentage build-up of radon-222 and thus to the percentage emanation and may be calculated from two measurements at suitable times. The use of drill-core samples allows the partial assessment of radon problems before mining begins. The measured radon emanation from individual samples ranges from less than 1% to 91%. The average values of samples from various domestic mining areas range from 8% to 57%. Factors appearing to affect emanation are: (1) porosity and permeability; (2) ore grade; (3) uranium mineral species (seldom controlling); (4) crystal or particle size; (5) lithology (carboniferous rock emanates less than sandstone, mudstone emanates more); (6) radium mineralogy; (7) geologic age; (8) mobility of deposits; and (9) moisture content. The dominance of one or more of these factors determines the effectiveness of specific control measures.

The potential burden of radon-222 and its daughters in a mine atmosphere depends on a number of parameters, one of which is the percentage of radon that may emanate. This laboratory study was undertaken to measure the emanation of radon from ore and rock samples selected from various mines and mining areas in the United States of America. Data derived from this study are used to evaluate the effects of various factors on radon emanation into mine openings.

In undeveloped mining areas where no mine workings exist, field methods are impractical. Yet radon control is such an important economic consideration that its cost may be decisive in determining mining methods (underground, open pit, or solution mining) or even whether or not a given deposit is mined at all.

To date, the project has covered most of the major areas of underground uranium mining in the USA. Samples from a few less important areas were also studied.

In all, nearly 800 samples from 100 mines and drilling areas in 25 'ore reserve areas', as defined by the United States Atomic Energy Commission, were studied. The coverage ranges from only one sample from some mines to 250 samples from the Ambrosia Lake area, 71 of which were from the Dysart No.1 mine.

Sampling has been more or less random. Most samples were obtained through the courtesy of the United States Atomic Energy Commission, Grand Junction Office, and had been collected for other purposes over the past 20 years. About 20% were specifically collected for this study.
In this study, radon is measured indirectly by the gross gamma activity of its daughters, lead-214 and bismuth-214. A shielded sodium iodide crystal is used to detect the gamma rays. The method used is a slight modification of the gamma-only method of radiometric assaying for equivalent uranium described by Scott and Dodd [1]. In fact, a radiometric assay is obtained for each sample. The only significant differences are: (1) Relatively inhomogeneous pieces of rock are used rather than pulverized and blended samples, and (2) the percentage increase in gamma activity from sealing time (time zero) to essential equilibrium is obtained.

The emanation values are based on the fact that radon, which would escape under natural conditions, is sealed in a container. It is assumed that the sample has not been recently subjected to changes significantly affecting emanation. After sealing, radon-222 accumulates in the container, and an equilibrium is reached when the accumulation is balanced by decay. The percentage increase in gamma activity due to short-lived daughters from time zero to equilibrium is equal to the percentage build-up of radon in the container which, at equilibrium, is equal to the percentage that emanates and would escape from the sample if the container was not sealed.

In practice, pieces of ore or mineralized rock are weighed, placed in metal containers 2 in (about 5 cm) in diameter and 1½ in (nearly 4 cm) high, with friction lids, and sealed with 100% solids epoxy resin. Ideally, the sample should conform closely to the size and shape of the container, but samples of various shapes and ranging in weight from less than 20 g to more than 100 g have been used. The samples are wedged into the tins with styrofoam or other soft, resilient material. A label affixed to the lid identifies the sample and serves to maintain rotational orientation in the counting chamber for successive counts.

All measurements, including background, are for 100,000 counts or 100 s, whichever is longer, unless extremely rich samples reach the 2-million-count capacity of the scaler in a shorter time. An initial measurement is made 4 to 8 h after sealing; rarely, initial measurements have been delayed up to 28 h after sealing. Since the half-life of radon-222 is 3.825 d, the second measurement is not made until at least 4 d after sealing when more than half the build-up of radon has occurred. From these two measurements, accurate extrapolations to time zero and equilibrium may be made.

Sealing time and the start of each measurement are recorded to the nearest minute. Time to accumulate the predetermined count is recorded to the nearest 0.1 s. Counts per second and subsequent values are calculated to three decimal places to minimize rounding errors. Data of a typical printout are as follows:

<table>
<thead>
<tr>
<th>Sample number</th>
<th>2549C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{226}$Ra</td>
<td>0.137 µg</td>
</tr>
<tr>
<td>Standard error (of data immediately above)</td>
<td>0.345%</td>
</tr>
<tr>
<td>$^{4}$U$<em>{3}$O$</em>{8}$</td>
<td>1.419%</td>
</tr>
<tr>
<td>Emanation</td>
<td>28.180%</td>
</tr>
<tr>
<td>Standard error (of data immediately above)</td>
<td>0.358%</td>
</tr>
<tr>
<td>Emanation per gram of sample</td>
<td>1139.716 pCi/g</td>
</tr>
</tbody>
</table>
This method is rapid and inexpensive. Time and cost should approximate those of gamma-only radiometric assays involving similar counting times. Counting times range from less than 1 min for high-grade samples to about 3 h for slightly mineralized samples. With the instrumentation used, a 116-g sample of a 1% uranium pulp standard, NB 73, from New Brunswick Laboratories, produces about 1000 counts/s after reaching equilibrium. About 5 h are required to accumulate 100,000 counts from the background.

Reproducibility is illustrated by samples processed once, then opened, placed in new containers, resealed, and reprocessed (Table I). These samples were randomly selected for recanning and range in grade from about 0.16% eU₃O₈ to about 21.00% eU₃O₈. They were resealed in new tins in approximately their original position, but rotational position was not maintained between runs.

For samples assaying more than about 0.05% eU₃O₈, the emanation values appear to be reproducible within a range of about 2%, perhaps not quite as good as shown here. For lower-grade samples, the reproducibility falls off rapidly as background fluctuations become increasingly significant. No direct comparisons have been made with more conventional methods, but the accuracy appears adequate for this study.

Thompkins [2] has estimated that the ores of Ambrosia Lake, N. Mex., release into mine openings 100 times more of the radon produced than do the ores of Elliott Lake, Ontario. Results from the more important areas of the present study are summarized in Table II. The emanation coefficients of individual samples range from less than 1% to 91%. The maximum differences are at least a hundredfold. Among the well-studied areas, the average emanation values range from 8% for the Chinle ores of Southwest Lisbon, Utah, to 57% for the Eocene ores of Monument Hill, Wyoming, a maximum of about sevenfold.

### TABLE I. REPRODUCIBILITY OF RESULTS ILLUSTRATED FOR THREE ORE SAMPLES EACH PROCESSED TWICE

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Sealed</th>
<th>Initial count</th>
<th>Final count</th>
<th>Per cent emanation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day</td>
<td>Hour</td>
<td>Day</td>
<td>Hour</td>
</tr>
<tr>
<td>1</td>
<td>134</td>
<td>07.34</td>
<td>138</td>
<td>14.07</td>
</tr>
<tr>
<td>2</td>
<td>144</td>
<td>07.24</td>
<td>149</td>
<td>08.34</td>
</tr>
<tr>
<td></td>
<td>Sample No. 2627</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>136</td>
<td>07.28</td>
<td>136</td>
<td>11.58</td>
</tr>
<tr>
<td>2</td>
<td>144</td>
<td>07.26</td>
<td>144</td>
<td>15.15</td>
</tr>
<tr>
<td></td>
<td>Sample No. 2643</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>121</td>
<td>07.27</td>
<td>127</td>
<td>14.53</td>
</tr>
<tr>
<td>2</td>
<td>134</td>
<td>07.23</td>
<td>138</td>
<td>13.10</td>
</tr>
<tr>
<td></td>
<td>Sample No. 2774C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE II. RADON EMANATION FROM URANIUM ORES FROM VARIOUS SITES

<table>
<thead>
<tr>
<th>Area</th>
<th>Number of samples</th>
<th>Per cent emanation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Ambrosia Lake, N. Mex.</td>
<td>250</td>
<td>56</td>
</tr>
<tr>
<td>Laguna, N. Mex.</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Black Jack, N. Mex.</td>
<td>7</td>
<td>55</td>
</tr>
<tr>
<td>Gallup, N. Mex.</td>
<td>7</td>
<td>92</td>
</tr>
<tr>
<td>SW Lisbon, Utah (Chinle formation)</td>
<td>99</td>
<td>58</td>
</tr>
<tr>
<td>SW Lisbon, Utah (Cutler formation)</td>
<td>15</td>
<td>49</td>
</tr>
<tr>
<td>NE Lisbon, Utah</td>
<td>3</td>
<td>38</td>
</tr>
<tr>
<td>Uravan, Colo.</td>
<td>69</td>
<td>47</td>
</tr>
<tr>
<td>Gas Hills, Wyo.</td>
<td>114</td>
<td>81</td>
</tr>
<tr>
<td>Shirley Basin, Wyo.</td>
<td>87</td>
<td>83</td>
</tr>
<tr>
<td>Crooks Gap, Wyo.</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td>Monument Hill, Wyo.</td>
<td>70</td>
<td>91</td>
</tr>
<tr>
<td>Turnercrest, Wyo.</td>
<td>5</td>
<td>53</td>
</tr>
<tr>
<td>Eastern Margin, Colo.</td>
<td>14</td>
<td>31</td>
</tr>
</tbody>
</table>

As stated by Starik and Melikova [3], "The phenomenon of emanation is extremely complex". Factors appearing from the present study to affect emanation are as follows:

1. **Porosity and permeability.** These properties were not measured, but porosity was estimated visually and from previous petrographic studies. Ores considered least porous are the low emanators from Elliott Lake, Ont., Southwest Lisbon, Utah (Chinle), and Eastern Margin, Colo. Cementation by silica and carbonate, respectively, reduces porosity in the first two; the last is a vein deposit.

2. **Ore grade.** In samples containing more than a few per cent uranium as uraninite (pitchblende), or coffinite, the ore mineral itself must be considered a cementing material. Although emanation does not show close continuous inverse variation with grade, samples containing more than a few per cent uranium tend to emanate much less of the radon produced than do those containing less than 1% or 2%.

3. **Uranium mineral species.** Starik and Melikova [3, 4], Gilletti and Kulp [5], Barretto [6] and others have determined variations in emanation with mineral species. Nonetheless, mineral species seldom controls the emanation rate from ores because, as observed by Starik and Melikova, emanation from ores is almost always greater than from the pure mineral.
For example, samples of ore from the coffinite district of Ambrosia Lake emanate as much as 57%, whereas a sample from the White King mine, Lakeview, Oreg., mineralized with massive, botryoidal, spherulitic coffinite (Fig. 1), emanates only 1%. Furthermore, less than 1% emanation has been determined for several samples of massive uraninite (pitchblende) from Southwest Lisbon, Utah, whereas an emanation as high as 91% is found in samples from Monument Hill, Wyo., containing uraninite and minor coffinite.

(4) Crystal or particle size. Tanner [7] states that particles larger than about micrometer size can retain almost all recoil atoms. Individual coffinite spherulites in Fig. 1 range upward to nearly 100 μm across and coalesce into larger masses. Figure 2 is an electron micrograph of another part of the same sample; the largest of the coalescing spherulites is about 60 μm across. Figures 1 and 2 may be compared with Fig. 3, which shows about 1-μm spherulites of coffinite from the Buckey mine, Ambrosia Lake, N. Mex.; this sample emanates about 20%. Similar relationships between emanation and particle size hold for uraninite (pitchblende). Figure 4 is an electron micrograph of a uraninite-bearing coating on a sand grain from a Powder River Basin, Wyo., ore sample that emanates about 75%. Figure 5 shows a coating of uraninite with minor coffinite on a sand grain from a Shirley Basin, Wyo., ore sample that emanates about 70%. In contrast, the emanation coefficients of massive uraninite (not illustrated) from Southwest Lisbon Chinle ores, with individual masses measured in millimetres or centimetres, range from less than 1% to about 12%.
(5) Lithology. Coalified wood tends to emanate less radon, and mudstone tends to emanate more radon than associated sandstones. Prutkina and Shashkin [8, 9] attribute the low emanation of coals to adsorption of radon within the coal. With increased uranium grade, i.e. the replacement of coalified wood by massive uranium minerals, relatively low emanation is maintained. The relatively high emanation of most mudstones seems incompatible with their low permeability. However, Granger [10] has found that radium tends to concentrate in mudstones. It is probably merely adsorbed; thus, most radon produced escapes by recoil.

(6) Radium-bearing minerals. Radium, which may escape from a uranium mineral, is unlikely to enter the crystal lattice of any mineral species except barite, celestite, or anglesite. From sound crystals of these minerals, only near-surface radon atoms can emanate. The emanation coefficients of three samples in which the only visible radioactive mineral is radiobarite range from 4% to 12%.

(7) Geologic age. Table II indicates that, among adequately sampled areas of sandstone ores, those in the oldest, Triassic, rocks emanate least, and those in the youngest, Tertiary, rocks emanate most. A possible cause is increased induration of the host rock with age. If the uranium
deposits in the older rocks are also older, an increase in the crystal or particle size of uranium minerals with age may also be a factor. However, at Ambrosia Lake, no difference in emanation could be demonstrated between a few samples of 'primary' or 'trend' ore and a comparable number of samples of supposedly younger 'redistributed' or 'stack' ore. On the other hand, ores in the Brushy Basin Member of the Morrison formation were found to emanate slightly more than those in the older Westwater Canyon Member.

(8) Mobility of deposits. Table II shows that the emanation from the Shirley Basin ores is nearly twice that from the Gas Hills ores; yet both are in the same Tertiary Wind River formation. The reason for this difference is unknown. Mr. John W. King, formerly with the United States Atomic Energy Commission (oral communication), considers the Gas Hills deposits to be relatively stable and the Shirley Basin deposits to be relatively more mobile, as evidenced in part by the more common and greater radiometric versus chemical disequilibrium (i.e., between radium and uranium) at Shirley Basin. Starik and Melikova [3] and Malyshev [11] note the differential movement of uranium and radium, which would produce disequilibrium. In any event, dissolution of uranium minerals will release
radium, which is unlikely to be reincorporated into a uranium mineral. If radium does not enter the crystal lattice of some other mineral such as barite, radon will emanate freely. It is evident, however, that the disequilibrium and emanation do not go hand in hand; rather, both are likely to be greater in a recently mobilized deposit.

(9) Moisture content. Although a detailed description is beyond the scope of this discussion, the results of a limited study of the effects of moisture content on emanation are in general agreement with those of previous workers. The emanation appears to vary only slightly with moisture content between about 10% and 80% saturation. The moisture content of ore in the mines is probably never less than 10% of saturation. About 80% saturation, water flow or capillarity, and transpiration are believed to dominate over emanation and diffusion in releasing radon into the mine atmosphere. Therefore, variations of emanation with moisture content as measured in the laboratory appear to have little application to actual conditions in the mines.

This uncompleted study, using a slight modification of the gamma-only method of radiometric assaying for equivalent uranium, has produced
rapid, inexpensive, and useful measurements of radon emanation from small pieces of uranium ore and mineralized rock. Maximum differences of more than a hundredfold have been found among individual samples, and as great as sevenfold differences among various mining areas. Some of the complexly interrelated factors responsible for these differences have been determined or reduced.

Because this method can utilize samples of drill core (and possibly cuttings), is non-destructive, and employs commonly available instrumentation, it may provide a low-cost evaluation of potential radon problems before mining begins. However, it should be supplemented by studies in the mines themselves, where possible, to evaluate gross factors such as air and water flow and the larger natural rock openings.

REFERENCES


DISCUSSION

S.R. AUSTIN: I would like to say that this study was designed by Mr. R.F. Droullard of the United States Bureau of Mines. However, since it was originally designed, he has more or less allowed me to carry it through in my own way.

The potential burden of radon-222 in radon daughters in a mine atmosphere depends on a number of parameters, one of which is the percentage of radon which may emanate.

A. GOODWIN: When you are calculating the percentage emanation, I assume you make a radiometric determination of radium which is a source of radon.

S.R. AUSTIN: No; I do not make a determination of radon, I make a determination of the short-lived daughters, which are lead-214 and bismuth-214. They come into transient equilibrium with radon very quickly. That is one of the reasons for delaying the initial count for four hours after sealing. Radium is not an intense gamma emitter. The radon daughters are the intense gamma emitters.

A. GOODWIN: But these are the ones that are supposedly trapped inside the rock.

S.R. AUSTIN: If the radon escapes before the daughters are born, then they are trapped inside the container and not inside the rock. They travel after the radium disintegrates and becomes radon, which is the only gas in the chain that can escape from the rock; the daughters are then solids. The only way that the daughters can escape from the rock is when they are, shall we say, in the womb.

A. GOODWIN: What I am trying to get at is, if you have up to 50% emanation from these rock samples, you have to take the emanation into account.

S.R. AUSTIN: Radium content is determined indirectly.

A. GOODWIN: Right! From the daughters of radon. While you have the rock out in the air, much of the radon being produced is escaping, up to 50%.
S. R. AUSTIN: That is correct. The only way that you can determine the radium is to determine it when the radon and its short-lived daughters come into equilibrium, which will be a matter of a few weeks. However, we do not wait as long as that because it will be more than half way towards equilibrium in four days so that, from a measurement after four days of sealing, timed precisely to the minute, we can extrapolate and find out what the content of radon daughters will be. The gamma activity of the radon daughters will be at equilibrium and from that we can then calculate the amount of radium.

R.L. ROCK: We all know that the dust of any radioactive ore will give us the ultimate in radon release if mineralization is discounted, so I wonder if you are taking this into consideration.

S.R. AUSTIN: Some work has been done on that. In the first place I should like to contrast the method given in this paper with Mr. Barretto's method. His method is more precise; the method I presented is what I would call a 'quick and dirty' method. For the purposes of this study I do not care whether the sample emanates 1%, 2% or 3%; I am interested in whether it emanates 1% or 10% or 30% or 60%.

I do not get very good precision with this method, but I think I have been able to demonstrate satisfactorily the differences in orders of magnitude. Furthermore, I have done some experiments with extremely high-grade thin samples, placing them on edge in the can or placing them flat in the can. There is quite a difference in radiometric grade. Provided one does not change the position of the sample between measurements, the difference in emanation is much less than the difference in grade. I might say of course that there are many factors which make this what I call a 'quick and dirty' method. One of these is that, as the radon escapes and then decays into its daughters, it is known that the daughters are in the can (or most of them), but their positions within the can are not. I am assuming that there is a statistical distribution with most of the radon daughters plated out onto some surface. Probably, a few more than otherwise are plated out within the rock; some are plated out onto the surface of the rock and onto the interior surface of the can. A few of them are still, of course, in the air within the can. But this is assuming that the distribution of the radon daughters in the can is (relatively only) comparable to what it was in the rock sample in the first place. This is not a precise method, but I think, as a practical method, it is useful.

G.R. YOURT: I wonder if you had thought of making measurements of emanation from radium co-precipitated with barium sulphate.

S.R. AUSTIN: I have not done that, but it has been reported in the literature. I think Mr. P. Dodd of the United States Atomic Energy Commission made some studies. I do not remember what the compound was and, as I recall it, he obtained a lower percentage emanation than I did from some of my higher-activity samples; but I think he quoted figures of around 70%.

I think that this depends to a large degree on what particle size you have in this type of precipitate. Apparently, about 1 μm or less is the size range for which a great many of the radon atoms can escape by fission recoil. As the particles become larger, fewer and fewer of the atoms can escape from a solid crystal by fission recoil. Of course, the variation in escape with increasing particle size is a power function and not a linear function.
R. L. ROCK: I am not trying to be critical, but it is very hard to make a radiometric analysis of a solid piece of rock with any degree of certainty. I wonder if you select samples which you consider quite homogeneous.

S. R. AUSTIN: No. The samples are taken as they are. A certain amount of preparing is done and lithological factors are noted, as is anything else that can be observed readily. In some cases, I am familiar enough with the sample to be able to record some things that are not directly evident. Otherwise, all these samples are treated alike. For one experiment, I used samples which were obviously stratified. It is known that uranium will be contained in certain beds or layers in the rock. So when I took these samples and sealed them into the can, I put the supposedly richer side next to the detector and determined the grade and the emanation. Afterwards I turned the samples over and remeasured. The measurements of inhomogeneous samples can differ by more than 2%, depending on whether the richer side or the poorer side is next to the detector. However, I still do not think that the differences noted (that is, those due to differences in position) are great enough to nullify the value of the determinations made.

W. GRAY: I would like to ask what fraction of the gamma rays would be absorbed at a distance equivalent to the thickness of a sample.

S. R. AUSTIN: I cannot answer this question. As I said, what is being done is to assume a rather statistical distribution for the radon daughters emanating, and to assume that a similar proportion of these daughters (plating out in various places or remaining in the atmosphere within the can) would be absorbed, as would be true for the original unsealed sample. This is an assumption but, may I repeat, we are not trying to be very accurate or very precise.

P. M. C. BARRETTTO: I think that the energies of the gamma rays that you are measuring are of the order of 1.76 MeV, which for a normal density of 2.6 g/cm$^3$ would have a range of at least 25 to 30 cm. I think the self-absorption would be very small, less than 5% to 10%.

W. GRAY: If this is true, I think that the method could be fairly accurate, i.e. it could have about the accuracy that is shown by the repeatability.

P. ZETWOOG: In the experiment with the 250 samples (your Table II), do you know the extent to which these results would be subject to statistical development? Does the pattern follow a Gaussian law?

S. R. AUSTIN: I do not know the law of distribution of the various values in this range. I can make some remarks about some of the other samples and some of the other areas. For instance, in the case of Southwest Lisbon, Utah, we had 99 samples showing a rather strange distribution. The high emanation value is 58%, the low value is less than 1%, the mean is 8%, which is rather strange. This is due entirely to one sample which is from the same district but has an altogether different lithology. Most of the samples from this district are more or less cemented by calcite. This particular sample was not; it was from an outlying part of the district and so the statistical distribution is rather strange. I might also remark on the results for Crooks Gap, Wyo. There is a high emanation value of 35%, a low value of 1% and a mean of 14%, which is rather on the low side. In this area, data are quite biased because of the samples available. A great many of them were fossil wood, which is a low emanator; and so the mean is lower than it would be if we had a normal sampling.
H.P. RICHARDSON: I would like to make a comment about the purpose of this work. In the first place, it was to get an idea of the probable emanation rate from the various areas and possibly also from specific mines, so that conclusions could be drawn for future mine development. If information can be provided to the people who will be developing the mines and if it gives them some indication of how much radon protection they could expect to have to provide for in mines that will develop in the future, our aim will have been satisfied.
1. INTRODUCTION

Radon monitoring and control in certain underground uranium mines is an important economic factor since its cost may be decisive for ore recovery. Thus, research towards understanding the factors controlling emanation and a study of the means of reducing it would be of practical and economic significance. The results of such research would also be of interest to those working in low-level counting facilities of laboratories and hospitals.

Very few data on the characteristics and percentages of radon escape from radioactive minerals (not to be confused with radon flux to the atmosphere) are found in the literature. This summary is based on the three papers in these Proceedings dealing with this subject (IAEA-PL-565/1, 3 and 8) and on discussions of the Panel.

2. FACTORS CONTROLLING EMANATION

Mineralogy, particle size, porosity and permeability, uranium distribution, weathering, and type of rock are positively related to radon emanation. On the other hand, there are factors such as ore grade, geologic age, moisture content and ambient temperature which appear to have no conclusive influence on the emanating power of the materials.

2.1. Particle size and emanation

The above-mentioned papers agree that crystal or particle size is an important factor affecting radon release into the mine atmosphere. This is of particular importance when mill tailings are used as a back-fill material. As an example, it was observed in one case that tailings with fractions of less than 40 \( \mu m \) released 10-15 times more radon than more coarse fractions.

2.2. Porosity and permeability

Paper IAEA-PL-565/8 indicates that for three different uranium provinces the ores considered least porous (estimated visually and by petrographic studies) corresponded to low emanators.

2.3. Uranium distribution

When the element uranium is found in specific uranium minerals or located within uranium-rich accessory minerals the radon produced has little chance of escaping. However, when the uranium-rich phase is coating the grains or found in the porous media of the rock the radon escape is larger.

2.4. Weathering

Weathered specimens of both rocks and minerals showed a larger percentage of radon escape than did otherwise identical fresh specimens from
the same respective areas (paper IAEA-PL-565/1). The phenomenon seems to be related to the destruction of the crystal lattice bounds and the mobilization of the uranium and radium to places where the radon produced can easily escape.

2.5. Type of rock

Among the 'hard rocks', basic and ultrabasic types emanate least. Among sedimentary rocks, shales and 'muddy' rocks emanate more than carbonates and clean sandstones.

2.6. Relationship between $^{222}\text{Rn}$ escape and uranium ore grade

Research on small samples indicated that apparently there is no direct relationship between the uranium concentration and the percentage of radon escape. No such relationship was observed either for individual mineral specimens (IAEA-PL-565/1), ore specimens (IAEA-PL-565/8), or in the actual mine atmosphere (IAEA-PL-565/3).

2.7. Moisture content

The practical influence of moisture content in the range likely to be found in mines is small until the point is reached where capillarity, evaporation and water flow dominate over emanation.

2.8. Geologic age and emanation

No conclusive results were obtained for ores indicating correlations between geologic age and percentage of emanation. However, such a correlation seems to exist in common igneous rocks and for certain types of uranium-bearing accessory minerals. A theoretical explanation which could support such a relationship has been suggested.

3. PERCENTAGE OF RADON ESCAPE

Rocks: 1-20%, average: 8%
Uranium ores: 1-90%, average: 25%

The percentage of radon escape depends on several physical parameters as seen above, which are particular to each type of ore. Thus, a parameter which is significant for one sample, e.g. porosity, may not be as important for another sample.

These percentages of radon escape in fresh materials are larger than the escape rates observed for other, non-radiogenic, noble gases although these gases have smaller atoms, are lighter and are not limited by a short half-life. Thus, some peculiar parameters appear to control the radon escape. Radiation damage has been suggested as one of them (IAEA-PL-565/1).
4. PRACTICAL APPLICATIONS TO THE URANIUM INDUSTRY

Before operation is started in a new mine the magnitude of radon control problems can be evaluated at reasonable cost from laboratory emanation studies of drill-core samples and from investigation of the nature of the host rock.

5. RECOMMENDATIONS FOR FURTHER STUDY

Research in the following directions is recommended:

(a) Estimation of radon control measures needed and of their cost before operation is started in a new mine;
(b) Determination of the appropriate tailing material to be used for back-fills and other mine construction works;
(c) Experimental determination of the radon flux from the mine walls, the access galleries (barren rock) and ore-grade material of various types;
(d) Selection of the best sealants or adsorbents to be used when closing old mine workings or covering the mine walls.
GENERAL RECOMMENDATIONS TO THE
INTERNATIONAL ATOMIC ENERGY AGENCY

1. The IAEA should take steps to encourage ICRP (Committee 2) to publish its current recommendations on radiation standards applicable to uranium mines and effluents, particularly regarding radon, radon daughters, and radium.

2. There should be a uniformity of mine radiation standards and of the application of these standards among the uranium-producing countries of the world; developing countries, which in the future may become uranium producers, should take note of the uniformity of mine radiation standards and, if possible, adopt these uniform standards.

3. The IAEA should sponsor research and development on instrumentation for monitoring and control of radiation in uranium mines, including personal dosimeters, and research into the behaviour and relative biological effects of radon and attached and unattached radon daughters. This research and development should be co-ordinated with studies in Member States.
LIST OF PARTICIPANTS

AUSTRALIA

J.W. Pearce
Australian Embassy, Massachusetts Avenue, Washington, D.C. 20036, United States of America

BRAZIL

P.M.C. Barretto
National Nuclear Energy Commission, Rua General Severiano 90, Rio de Janeiro, GB

CANADA

D.D. Bell
Eldorado Nuclear Limited, 151 Slater Street, Ottawa K1P 5H3, Ont.

W. Gray
Energy, Mines and Resources, Mining Research Center, Bells Corners, Complex Building 10, Ottawa K1A 0G1, Ont.

G.R. Yourt
120 Adelaide Street West, Toronto 110, Ont.

FRANCE

Y. François
Département de protection, Centre d'études nucléaires, B.P. 6, F-92260 Fontenay-aux-Roses

P. Zettwoog
Département de protection, Centre d'études nucléaires, B.P. 6, F-92260 Fontenay-aux-Roses
LIST OF PARTICIPANTS

SOUTH AFRICA

A.C. Haasbroek
Mines Surveyors Section,
Department of Mines,
Pretoria

UNITED STATES OF AMERICA

S. R. Austin
Bureau of Mines,
Room 3, Building 12,
USAEC,
Grand Junction, Colo. 81501

A. Goodwin
Mining Enforcement and Safety Administration,
Department of the Interior,
Washington, D.C. 20240

R. H. Kennedy
Division of Production and
Materials Management,
USAEC,
Washington, D.C. 20545

F. E. McGinley (Chairman)
Engineering and Safety Branch,
Administrative Services Division,
USAEC,
Grand Junction, Colo. 81501

S. A. McGuire
Occupational Health Standards Branch,
Directorate of Regulatory Standards,
USAEC,
Washington, D.C. 20545

C. Palmiter
Criteria and Standards Division,
Office of Radiation Programs,
Environmental Protection Agency,
Washington, D.C. 20545

J. A. Patterson
Division of Raw Materials,
USAEC,
Washington, D.C. 20545

H. P. Richardson
Office of Assistant Director of Mining
Research,
Bureau of Mines,
Department of the Interior,
Washington, D.C. 20240
R. L. Rock
Radiation Group,
EMS-Denver Technical Support Center,
Mining Enforcement and Safety Administration,
Department of the Interior,
Building 20, Denver Federal Center,
Denver, Colo. 80225

The Honorable G. F. Tape
Associated Universities Inc.,
1717 Massachusetts Ave., N.W.,
Washington, D.C. 20036

Scientific Secretary

J. Cameron
International Atomic Energy Agency,
Vienna, Austria
HOW TO ORDER IAEA PUBLICATIONS

Exclusive sales agents for IAEA publications, to whom all orders and inquiries should be addressed, have been appointed in the following countries:

UNITED KINGDOM  Her Majesty's Stationery Office, P.O. Box 569, London SE 1 9NH
UNITED STATES OF AMERICA  UNIPUB, Inc., P.O. Box 433, Murray Hill Station, New York, N.Y. 10016

In the following countries IAEA publications may be purchased from the sales agents or booksellers listed or through your major local booksellers. Payment can be made in local currency or with UNESCO coupons.

ARGENTINA  Comisión Nacional de Energía Atómica, Avenida del Libertador 8250, Buenos Aires
AUSTRALIA  Hunter Publications, 58 A Gipps Street, Collingwood, Victoria 3066
BELGIUM  Service du Courrier de l'UNESCO, 112, Rue du Trône, B-1050 Brussels
CANADA  Information Canada, 171 Slater Street, Ottawa, Ont. K 1A 0S 9
C.S.S.R.  Alfa, Publishers, Hurbano nové námestie 6, CS-80000 Bratislava
FRANCE  Office International de Documentation et Librairie, 48, rue Gay-Lussac, F-75005 Paris
HUNGARY  Kultura, Hungarian Trading Company for Books and Newspapers, P.O. Box 146, H-1011 Budapest 92
INDIA  Oxford Book and Stationery Comp., 17, Park Street, Calcutta 16
ISRAEL  Heiliger and Co., 3, Nathan Strauss Str., Jerusalem
ITALY  Libreria Scientifico, Dott. de Biasio Lucio "aeiou", Via Meravigli 16, I-20123 Milan
JAPAN  Maruzen Company, Ltd., P.O.Box 5050, 100-31 Tokyo International
NETHERLANDS  Marinus Nijhoff N.V., Lange Voorhout 9-11, P.O. Box 269, The Hague
PAKISTAN  Mirza Book Agency, 65, The Mall, P.O.Box 729, Lahore-3
POLAND  Ars Polona, Centrala Handlu Zagranicznego, Krakowskie Przedmiescie 7, Warsaw
ROMANIA  Cartimex, 3-5 13 Decembrie Street, P.O.Box 134-135, Bucuresti
SOUTH AFRICA  Van Schalk's Bookstore, P.O.Box 724, Pretoria
SPAIN  Nautrónica, S.A., Pérez Ayuso 16, Madrid-2
SWEDEN  C.E. Fritzes Kungl. Hovbokhandel, Fredsgatan 2, S-10307 Stockholm
U.S.S.R.  Mezhdunarodnaya Kniga, Smolenskaya-Sennaya 32-34, Moscow G-200
YUGOSLAVIA  Jugoslovenska Knjiga, Terazije 27, YU-11000 Belgrade

Orders from countries where sales agents have not yet been appointed and requests for information should be addressed directly to:

Publishing Section,
International Atomic Energy Agency,
Kärntner Ring 11, P.O.Box 590, A-1011 Vienna, Austria