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Meteorological Consequences of Atmospheric Krypton-85

Krypton-85 can disturb the atmospheric environment by perturbing atmospheric electrical processes.

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Natural atmospheric processes involving air ions will be perturbed if the ionization due to reactor by-products in the atmosphere approaches the ionization produced by background radiation. Projections indicate that ^{85}Kr, a radioactive, chemically inert gas, may be produced and released in such quantities that it will create atmospheric ions at rates comparable to the present ion production rate near the tropical ocean surface. This article concerns the possible effects of ^{85}Kr on atmospheric electrical phenomena and air ions. Calculations based on a simple model for the global atmospheric electric circuit indicate that the total electric resistance between the earth and the ionosphere could decrease measurably within the next 50 years. Mechanisms by which a disturbance of atmospheric electric properties could lead to a form of inadvertent weather modification are briefly discussed.

Properties of Krypton-85

Krypton-85 is a long-lived radioactive gaseous by-product of nuclear fission produced in high yield in nuclear fission reactors and explosions (*1*, p. 5). A large increase in the production rate of ^{85}Kr seems inevitable as more nations turn to nuclear power to produce energy. Almost all the ^{85}Kr remains in sealed nuclear fuel elements until the elements are chemically dissolved to reprocess the fuel or to separate plutonium. At present, radioactive inert gases are released to the atmosphere in a controlled manner to be diluted by normal atmospheric mixing.

Krypton-85 releases have been thought to be justified by its properties. It is chemically inert (except for reaction with fluorine at high temperatures and pressures), which limits its interactions in the biosphere (*2*) to physical solution, particularly in nonpolar solvents (fats and oils), in which its solubility is highest; absorptive phenomena; and possibly clathrate formation. These interactions all require a continuing concentration of ^{85}Kr in the surrounding atmosphere. Concentration in the biota, such as is found with chemically or metabolically active species, does not occur. Krypton-85 is essentially a pure beta-emitting isotope, with its beta particle, of maximum energy 0.672 Mev, emitted in 99.6 percent of the nuclear transformations. The decay product is a stable rubidium isotope. The principal beta, which delivers essentially all of the radiation dose, has an average energy of 0.249 Mev and a maximum range in air of about 1.2 m. Radiation exposure is primarily to the skin and superficial tissues (the maximum penetration in tissue is 2 mm and the average penetration about 0.2 mm) although the convention of the International Commission on Radiological Protection for determining permissible concentrations of noble gases considers the exposure to be to the whole body. Recent experiments indicate, however, that internal exposure may also be significant and that the lung or hematopoietic system could be the critical organ (*3*). The maximum permissible airborne concentration, $(\mathrm{MPC})_a$, of ^{85}Kr in unrestricted areas is 300 nanocuries per cubic meter.

The radioactive half-life of ^{85}Kr is 10.76 years, which, in the absence of significant mechanisms for removal of the isotope once it is released (*1*, p. 16), means that it will accumulate in the atmosphere until radioactive decay balances release. Assuming average meteorological conditions, a single nuclear fuel reprocessing plant could release on the order of 10 megacuries of ^{85}Kr annually without exceeding the $(\mathrm{MPC})_a$ at the boundary of its controlled area (*4*) and could, therefore, be responsible for an equilibrium accumulation of about 155 megacuries of ^{85}Kr in the atmosphere.

Atmospheric Ionization

The absence of removal mechanisms for krypton and its relatively long radioactive half-life produce a distribution of radiation due to ^{85}Kr which is different from that of natural background radioactivity and radioactive fallout. Natural radioactivity due to uranium, thorium, and their decay products, which are found in the rocks and sands in all parts of the world, produces ions in an air layer near the ground. In addition to ground level radioactivity, cosmic rays and airborne isotopes create ion pairs in the volume of the atmosphere. Cosmic-ray–produced ions have a distribution with a minimum at sea level. The minimum production rate for ions produced by cosmic rays is about 1.5×10^6 ion pairs per cubic meter per second at sea level on the tropical oceans (*5*, p. 575).

The atmosphere normally contains a number of isotopes such as tritium, ^{14}C,

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^{22}Na, ^{32}P, ^{7}Be, ^{33}P, ^{35}S, ^{85}Kr, radon, thoron, and the decay products of radon and thoron. At present these isotopes, with the exception of radon and its daughter products in continental air masses, do not make a significant contribution to the ion background. The radon content of an air mass depends in a complex way on meteorological conditions, including the prior history of the air mass. Because the longest radioactive half-life of a radon isotope is 3.8 days, a significant atmospheric concentration occurs only near a continuous source of radon, such as uranium-bearing rocks and soil. When a continental air mass is swept over the open oceans or polar ice caps, it is cut off from a supply of fresh radon while radioactive decay reduces the radon concentration. Although some radioactive daughter products of radon remain, these products are attached to aerosol particles and are effectively removed by rain or as fallout. Consequently, the air near the surface in remote regions of the oceans and polar caps, cleansed of most of the natural radioactivity and aerosol particles, has an ionization profile determined by the cosmic-ray distribution. Even though the concentration of radon may increase with altitude (*6*) over the oceans, radon above a few kilometers from the surface is not a significant ionizing agent compared to cosmic rays.

Artificial radioactivity from nuclear weapons tests and nuclear reactors can contaminate the regions of clean oceanic air. The contamination of oceanic air by tropospheric fallout is limited because these radioactive isotopes are attached to aerosols which fall to the earth's surface, primarily within the latitude band of the test site. Radioactive fallout will produce a strong increase in the ionization very near the surface of the earth. The increase is expected to be significant for only 4 to 5 days (*7*) and to disappear within 9 days. In contrast, the 10.76-year radioactive half-life and the lack of significant removal mechanisms for ^{85}Kr ensure that it will contaminate the entire atmosphere of the earth, including previously uncontaminated masses of oceanic air. This source of ionization will be much more uniformly distributed vertically and horizontally and more permanent than fallout radioactivity.

Atmospheric Electric Model

The classic model for the electrostatic environment of the earth treats the earth's surface as one conducting plate of a leaky spherical capacitor (*5*, p. 379). Although the lower atmosphere is a very poor electrical conductor, the conductivity increases rapidly with altitude. The result is that above a certain altitude, the horizontal conductivity is sufficient to equalize the potential around the globe. Above this equalizing layer there is the equivalent of a spherical conducting region acting as the second plate of the global capacitor. The global capacitor is thought to be kept charged by electrical storms that transport a net positive charge aloft and leave the earth with a corresponding negative charge. It is continuously being discharged by conduction currents between the equalizing layer and the earth's surface. I will show that an accumulation of ^{85}Kr in the atmosphere will decrease the electrical resistance across the global capacitor.

Columnar resistance can be defined as the electrical resistance of a column of the atmosphere 1 m^2 in cross section connecting the earth's surface to the equalizing layer. Provided the conductivity is known as a function of altitude, the columnar resistance can be calculated from

$$R_c = \int dh/\lambda(h) \qquad (1)$$

where R_c is the columnar resistance (ohm m^2), $\lambda(h)$ is the atmospheric conductivity (mho/m), and h is the altitude above sea level. The integral is taken from zero to the equalizing layer. The columnar resistance is insensitive to the value of h used for the equalizing layer since the upper atmosphere is a good conductor.

The total resistance, R, across the global capacitor is obtained by integrating the columnar resistances, connected in parallel, over the surface of the earth. In order to perform a realistic computation of the total resistance, a knowledge of the conductivity profile over all portions of the surface of the earth is needed. Since conductivity measurements have been made for only a few points on the globe, a gross simplification must be made in order to proceed with the calculation of resistance. All continents will be assumed to have the same conductivity profile, and a value of columnar resistance, R_k, typical of continental air masses will be used. All oceans and snow- and ice-covered regions will be assumed to have the same conductivity profile and to have a value of columnar resistance, R_o, typical of maritime air masses. Since the transition from continental to maritime air mass is a gradual one, the ratio of land to ocean, snow and ice area, f_k/f_o, will be deliberately overestimated. This calculation of the fractional change in the global resistor, $\Delta R/R$, due to an increase in volume ionization will neglect the change in columnar resistance over the land areas, with the result

$$\frac{\Delta R}{R} = \frac{\Delta R_o}{R_o} \, \frac{1}{1 + f_k R_o/f_o R_k} = 0.82 \, \frac{\Delta R_o}{R_o} \qquad (2)$$

for $f_k/f_o = 1/3$ and $R_o/R_k = 2/3$. As a consequence of the equalization layer, any change in the columnar resistance above the oceans will strongly affect the resistance of the global capacitor and may also affect the potential difference across it, above the continents as well as over the oceans.

The volume electrical conductivity is due to atmospheric ionization. Assuming that n is the concentration of fast atmospheric ion pairs (ion pairs per cubic meter), the electrical conductivity λ is given by

$$\lambda = 2e\mu n \qquad (3)$$

where e is the electronic charge and μ is the mobility for fast ions of either sign (square meters per volt per second). The mobility of fast ions is inversely proportional to atmospheric density and consequently increases with height. This rapid increase of conductivity with height produces a columnar resistance to which the largest contribution is the resistance of the lower troposphere.

The ion concentration depends on the balance between the ion production rate and the rate of loss of ions through recombination and attachment to aerosol particles as

$$q = \alpha n^2 + \beta Z n \qquad (4)$$

where q is the ion pair production rate (ion pairs per cubic meter per second), α is the fast ion recombination coefficient (cubic meters per ion pair per second), Z is the number concentration of aerosols (number per cubic meter), and β is the ion-aerosol attachment coefficient (ions per particle per second). The accepted value of α is 1.6×10^{-12} m^3 per ion pair per second. The coefficient β depends on the size of the aerosol particles and is 8.2×10^{-12} ions per particle per second for ion attachment to an uncharged particle with a radius of 20×10^{-6} cm (*8*). Ion recombination dominates the process as the mean size and density of an aerosol become smaller.

The increase in ion production rate can be related to the concentration of ^{85}Kr since an ^{85}Kr concentration of 1 nc/m^3 produces an additional 2.85×10^5 ion pairs per cubic meter per second, assuming that the average energy per disintegration is 0.25 Mev and the average beta particle energy needed to produce each ion pair is 32.5 ev.

Over open oceans the additional ionization due to ^{85}Kr will be noticeable at concentrations well below the $(\mathrm{MPC})_a$ of 300 nc/m^3. For example, an ^{85}Kr concentration of 3 nc/m^3 will produce an additional 8.55×10^5 ion pairs per cubic meter per second, a 57 percent increase over the sea level ion production rate due to cosmic rays.

There are a number of reasons for choosing 3 nc/m^3 as a bench mark level for ^{85}Kr. First, at that concentration the perturbation of the ion production rate is roughly one-half of the background rate, which guarantees that effects of the perturbation will be distinguishable from background fluctuations. Second, 3 nc/m^3 is a convenient submultiple (1 percent) of the present $(\mathrm{MPC})_a$. Consequently, the health effects of ^{85}Kr at that level should be those expected for a whole-body radiation dose of 4.5×10^{-5} rem/year (*1*, p. 30). Third, a number of studies project atmospheric concentrations of the order of 3 nc/m^3 for ^{85}Kr in the early part of the next century (*1*, pp. 32–34; *4, 9*). Fourth, normal dilution in the atmosphere is used to reduce the concentration of ^{85}Kr in a controlled release to a concentration below the $(\mathrm{MPC})_a$. A background level of 1 percent is not likely to affect the method or quantities involved in individual ^{85}Kr releases.

The equilibrium concentration of fast ions produced by cosmic rays at sea level, assuming an aerosol background of 300×10^6 particles per cubic meter, is given by Eq. 4 as 466×10^6 ion pairs per cubic meter. If the ion production due to ^{85}Kr at 3 nc/m^3 is added to the cosmic-ray ionization rate the equilibrium density of fast ions becomes 665×10^6 ion pairs per cubic meter, an increase of 43 percent. Since by Eq. 3 the electrical conductivity is proportional to the ion density, the sea level electrical conductivity of clean oceanic air will increase by 43 percent because of the presence of ^{85}Kr at the bench mark concentration.

The columnar resistance can be calculated once the altitude dependence of the ^{85}Kr concentration is established. For the unperturbed conductivity profile, I will use a profile approximating the average of the positive and negative conductivities measured by Woessner *et al.* (*10*). I will use

$$\lambda = \lambda_0 \exp(0.238h) \qquad (5)$$

where $\lambda_0 = 2.8 \times 10^{-14}$ mho/m and h is in units of kilometers, as the conductivity profile due to cosmic rays. I expect that the concentration of ^{85}Kr will decrease with altitude in proportion to the density of air at each altitude. This type of profile leads to the conclusion that the perturbation in conductivity due to ^{85}Kr will be greatest at sea level and will be negligible when compared to the conductivity due to cosmic rays above 10 km. Experimental evidence on the vertical distribution of ^{85}Kr indicates that its concentration decreases only slightly faster than does the density of the atmosphere (*11*).

The assumed profile of conductivity in the presence of ^{85}Kr will have the form

$$\lambda = \lambda_0 \exp(0.238h) + C\lambda_0 \exp(-0.238h) \qquad (6)$$

where h is in kilometers and C is the percentage increase in the ion pair concentration due to a particular sea level concentration of ^{85}Kr. The first term is the cosmic contribution as given by Eq. 5. The use of the same scale factor in both exponents allows the columnar resistance, R_{co}, to be evaluated in closed integral form. Using Eq. 6, the integral from 0 km to infinity of Eq. 1 is

$$R_{co} = \frac{1}{0.238\lambda_0} \frac{1}{C^{1/2}} \left[\frac{\pi}{2} - \arctan\left(\frac{1}{C^{1/2}}\right) \right] \qquad (7)$$

This may be compared to the unperturbed columnar resistance integrated over the same limits to yield

$$R_0 = 1/0.238\lambda_0 \qquad (8)$$

The fractional change in columnar resistance will have the form

$$\frac{\Delta R_0}{R_0} = \frac{R_{co} - R_0}{R_0} = \frac{1}{C^{1/2}} \left[\frac{\Pi}{2} - \arctan\left(\frac{1}{C^{1/2}}\right) \right] - 1 \qquad (9)$$

Provided C is sufficiently less than 1, Eq. 9 can be written as a power series expansion

$$\frac{\Delta R_0}{R_0} = -\frac{C}{3} + \frac{C^2}{5} - \frac{C^3}{7} + \frac{C^4}{9} - \ldots \qquad (10)$$

If the ^{85}Kr concentration at sea level is 3 nc/m^3, the quantity $\Delta R_0/R_0 = -0.11$. With this value for $\Delta R_0/R_0$, the change in the resistance of the global capacitor as given by Eq. 2 is $\Delta R/R = 0.093$. Althouth the columnar resistance is an indirectly measured quantity, a shift of 10 percent from the average values for the last half-century should be easily measurable. In summary, if the accumulation of ^{85}Kr in the atmosphere is allowed to reach 1 percent of the $(\mathrm{MPC})_a$, a measurable global change in atmospheric electrical parameters will be produced.

Inadvertent Weather Modification

The complex interactions of the real atmosphere suggest that a substantial perturbation of ionization may affect a variety of other parameters. To date, very little has been published linking ^{85}Kr to atmospheric phenomena. This is probably due to the small number of scientists interested in atmospheric electricity and the general lack of awareness that mankind has the ability and apparent intention to release enough ^{85}Kr to change the atmospheric ionization background. Information related to this topic must be searched for in articles dealing with the atmospheric effects of cosmic-ray ionization or with electrical influences on the physical processes in clouds. As a result, there is no comprehensive theory with which to evaluate the net effect of ^{85}Kr releases on meteorological processes. There are, however, some clues indicating that the possible environmental effects deserve serious study. Although some of the material needs updating, a 1969 article (*12*) on electricity and weather modification is a valuable introduction. A more recent article (*13*) contains a section on the impact of cosmic-ray ionization on the atmosphere.

Several properties of ^{85}Kr indicate that its potential as a weather-modifying agent should be taken seriously. In contrast to most materials used for weather modification, ^{85}Kr will not be confined to a single area. Chemically inert ^{85}Kr will penetrate the entire atmosphere, so that its effects may be felt anywhere on the globe. Because of its long radioactive half-life, any effects will persist for decades. Atmospheric conductivity is coupled by Ohm's law with the atmospheric electric field and the ionospheric electric potential. In turn, the ionospheric potential is maintained by the balance between thunderstorm charging currents and the continual discharge through the global resistor. Unless thunderstorm electrification mechanisms are independent of the ambient electric field and related electrical phenomena, an electrical feedback loop could exist coupling thunderstorms at widely separated localities.

On the basis of current knowledge, there appear to be several pathways by which air ionization due to ^{85}Kr could have an environmental impact. Topics that require further investigation include the net effects of external influences on thunderstorm electrification (*14*); the electrically enhanced coalescence of cloud droplets to form raindrops, especially cloudbursts (*15*); and the formation of sulfate aerosol particles by gas-to-particle conversion mechanisms involving ions (*16*). Without a significant increase in research effort, it is likely that ^{85}Kr will accumulate in the atmosphere faster than our knowledge of related phenomena accumulates.

Conclusion

Nonradiobiological phenomena affected by ^{85}Kr include environmental radioactivity, atmospheric electricity, and inadvertent weather modification. If release of ^{85}Kr into the atmosphere continues unabated, global changes in the atmospheric electric circuit will occur within 50 years. Our present understanding of atmospheric processes is insufficient to determine the extent of consequent weather changes and whether they would be beneficial or harmful. Because of the 10-year half-life of ^{85}Kr, global changes may last decades.

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An Expanded Approach to the Problem of Disappearing Species

Species, as part of the common heritage, require common action to protect them.

Norman Myers

The problem of disappearing species has hitherto been tackled mainly from the standpoints of biology and ecology (*1*), with less attention to the economic and institutional factors that bring species under threat. Yet the principal destructive process at work now is modification or loss of species' habitats, which arises for the most part from economic development of natural environments. In this article I examine the problem from the economic and institutional perspectives, in order to identify opportunities for an expanded approach to conservation of species.

Animal species and subspecies at present known to science and recognized as threatened total slightly over 1000, with an extinction rate put at one per year (*2*), compared with a rate of roughly one every 10 years from 1600 to 1950 and a natural rate of perhaps one every 1000 years during the "great dying" of the dinosaurs. In addition, 20,000 flowering plants are thought to be at risk. The world's stock of all species is now estimated at 10 million, of which 8.5 million have still to be identified (*3*). The scale of the potential threat seems clear: if present land-use trends continue, and unless better conservation measures are implemented, society stands to lose a substantial part of its heritage in species and genetic resources within a few decades.

This article is based on the premise that such loss would be detrimental to human welfare. Our investigations of the genetic attributes of species are still in their early stages, but they have already contributed to modern agriculture, medicine and pharmaceuticals, and many industrial processes. Indeed the spectrum of species can be reckoned a repository of some of society's most valuable raw materials. Moreover, loss of species will affect generations into the indefinite future, whose options to utilize species in ways yet undetermined should be kept open. Yet certain sectors of the contemporary community have difficulty keeping themselves, let alone other species, in being, and I wish to emphasize this aspect of the situation. Whose needs are served by conservation of species, and at what cost to others?

Certain other trade-offs should be considered. Many temperate-zone environments have already been fundamentally modified. The disruption of North America's forests led to the extinction of the passenger pigeon, a species that could not adapt when its particular form of forest habitat disappeared, but it also led to the proliferation of the white-tailed deer, a successional species that thrives

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