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CONSIDERATIONS IN SITING LONG-TERM RADIOACTIVE NOBLE GAS STORAGE FACILITIES*

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CONSIDERATIONS IN SITING LONG-TERM RADIOACTIVE NOBLE GAS STORAGE FACILITIES[*]

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INTRODUCTION

Of those noble gases produced in nuclear reactor operations, only ^{85}Kr is considered to have significant long-term health effects because of its chemical stability, long half-life, high production rate, and its relative hazard. Figure 1 gives the projected production rate and total accumulation for ^{85}Kr through the remainder of this century (ORNL, 1970).

In normal operations, only minute quantities of ^{85}Kr are released at the reactor itself. Almost all of the ^{85}Kr is released at nuclear fuel reprocessing plants during the chopping and dissolving operations. At present, essentially all of this gas is released to the atmosphere. Figure 2 shows the projected individual dose rates for both skin and whole body resulting from exposure to accumulated ^{85}Kr, assuming present practices of atmospheric release are continued. At current levels of reactor operation, this practice is considered to be acceptable; however, based upon projections for future reactor usage and resultant exposures, it appears to be the general consensus that the practice cannot be allowed to continue indefinitely. Figure 3 shows the projected world-wide population dose based

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[*] Work performed under the auspices of the U.S. Atomic Energy Commission.

on data from the previous figure plus predicted world population growth (U.N., 1966). The point at which measures to prevent the release will become necessary has not as yet been defined, but it appears reasonable to assume that sooner or later routine release of ^{85}Kr to the atmosphere from fuel reprocessing plants will be prohibited.

COST-BENEFIT ANALYSIS

The application of cost-benefit analysis can be used to gain some insight into the advisability of instituting preventive measures. Table 1 gives some data on the effects of ^{85}Kr atmospheric releases. These data have been derived by assuming the following:

(1) Concentration-to-dose conversion factors have been calculated from data given by Dunster and Warner (1970). These are 1.4×10^4 and 2.1×10^6 rem/yr per Ci/m^3 for whole body and skin, respectively.

(2) The mass of the atmosphere is taken to be 5×10^{21} gm, which at conditions of standard temperature and pressure occupies a volume of 4.2×10^{18} m^3 (USGS, 1967).

(3) For this cost-benefit analysis we assume that the released ^{85}Kr mixes instantaneously with the entire atmosphere to a uniform concentration. The significance of atmospheric diffusion of released gas to the point of uniform mixing will be discussed later in this paper.

(4) The only process by which atmospheric levels of ^{85}Kr are diminished is by radioactive decay. Therefore, the mean atmospheric residence time for ^{85}Kr is essentially its mean radiological life, approximately 15.5 yr. This implies that there is no sink in nature that removes ^{85}Kr and renders it biologically unavailable.

It can be determined from these data that the total whole body dose resulting from each curie of ^{85}Kr released to the atmosphere will average

$$\frac{1.4 \times 10^{4}\ \frac{\text{rem-m}^3}{\text{Ci-yr}}}{4.2 \times 10^{18}\ \text{m}^3} \times 15.5\ \text{yr} = 5.2 \times 10^{-14}\ \text{rem/Ci}.$$

Determination of total population dose is based on an assumed uniform exposure to the entire world population taken as 3.5 billion people. Therefore, the total population dose integrated to infinite time is 1.8 × 10^{-4} man-rem per curie for whole body and 0.027 for skin.

The monetary cost for biological damage due to radiation exposure has been estimated by various authors to be somewhere in the low hundreds of dollars per man-rem (Cohen, 1973). For purposes of this report we have assumed a cost of $250 per man-rem for whole body exposure. For skin exposure this value is estimated at approximately $40 per man-rem based on the ratio (factor of 6) between the ICRP maximum permissible dose (MPD) criteria for whole body and skin (ICRP, 1966). This implies that roughly equivalent damage is done to an individual by his exposure to MPD levels of either 0.5 rem/yr to the whole body or 3.0 rem/yr to the skin. Using these data, one may estimate the cost for biological damage due to ^{85}Kr based on either whole body or skin exposure to be roughly \$0.05 or \$1.00 per curie, respectively. Essentially this implies that skin may be considered to be the critical organ for ^{85}Kr exposure. For each curie released to the atmosphere, the resultant biological damage cost to all humanity over all time is approximately one dollar. Expenditures for prevention of ^{85}Kr release in excess of this figure would therefore not be considered to be cost effective.

RELEASE PREVENTION COSTS

Having estimated the effect of ^{85}Kr release, we shall next estimate the cost of release prevention. Continued research has been performed on methods for ^{85}Kr removal and storage. Other papers given in this symposium deal extensively with this topic. Estimates on ^{85}Kr treatment costs have been provided by Slansky et al. (1969), Davis (1973), and Davis et al. (1973). From these data we shall conservatively assume that for a 1500 ton/yr fuel reprocessing plant, ^{85}Kr treatment facilities can be installed at a capital cost of \$2,000,000 and operated at a cost of \$200/ton of fuel processed. Further, assuming a plant life of 20 yr, an interest rate of 12%, and a content of 10^4 Ci of ^{85}Kr per ton of spent fuel, we calculate a prorated capital cost of approximately 2¢/Ci and an operating cost of 2¢/Ci, giving a total cost of 4¢/Ci for ^{85}Kr release prevention. Using this estimate, we have performed the cost benefit analysis shown in Table 2. Comparing estimated biological damage costs against release prevention costs, we derived a cost benefit ratio of roughly 25. This analysis also allows us to estimate the cost effectiveness for ^{85}Kr treatment to be \$220/man-rem of whole body dose averted, or roughly $1.50 for each man-rem of skin exposure averted. To gain some perspective on the significance of these figures, we may compare them with cost estimates for other activities. As previously discussed, a suggested guideline for cost effectiveness is considered to be $250/man-rem of whole body dose averted and $40/man-rem of skin dose averted. Hull (1972) has estimated a cost of between $1,000 and $1,000,000/man-rem averted as the cost for compliance with the currently proposed light-water reactor standards. It appears from these figures that, even under present conditions, it would be reasonable to require implementation of measures to prevent the release of ^{85}Kr from fuel reprocessing plants. Such a requirement certainly seems consistent with "low as practicable" guidelines, especially when compared to the proposed standards for light-water reactors.

STORAGE OPTIONS

In any event, whenever prevention of atmospheric release becomes a requirement, some options for the accomplishment of this objective must be evaluated. These are diagrammed in Fig. 4. Having decided to retain rather than release ^{85}Kr, we must consider whether to do so in some concentrated form or to retain the entire offgas volume in which it is carried.

Another option is whether or not to store the gases at the surface or at an underground storage facility. The main tradeoff here is between greater assurance of retention plus easier surveillance at surface facilities as opposed to lower cost for underground storage.

Finally, we must decide whether to store the retained gas at the point of collection or to transport it to a centralized facility specifically designed for long-term storage. Selection of the best options will depend on prevailing costs and political attitudes at the time the decision is made. At such time, a thorough cost-benefit analysis of the various options should, of course, be made. We shall not attempt such an analysis here. For purposes of this study we shall assume that ^{85}Kr is extracted from fuel reprocessing offgas streams and stored in pressurized tanks at a centralized facility for the extended periods of time necessary to allow for decay to innocuous levels. This assumption would appear to be consistent with present AEC philosophy as expressed in its nuclear waste management policy, in which storage of solidified high-level waste at centralized repositories is required (Fed. Reg., 1970).

SITING CRITERIA

Anticipating the need for some centralized radioactive noble gas storage facility, we have reviewed some of the factors that might be considered in developing optimum siting criteria. The facility we envision will be used for the receipt and long-term storage of pressure tanks of extracted noble gas that have been collected at various fuel reprocessing plants throughout the country and perhaps the world. From the work of Dunster and Warner (1970) and from various other considerations, it would seem reasonable to assume that each tank or container of gas would initially contain approximately 1 MCi of ^{85}Kr. On this basis, roughly 20 containers per year would be generated at present, and by the turn of the century this figure would rise to approximately 80 containers per year. At 1 MCi per container, the output of decay heat would be no more than

1.6 kW, which should prove to be quite manageable, with cooling accomplished either by submersion of the containers in water or by maintaining sufficient air flow in the storage area to dissipate this heat by convection.

In determining safety criteria for siting the storage facility, we have assumed that in normal operation there would be no routine releases of radioactive gas. The only assumed mechanism for release would be from accidental or inadvertent containment failure.

With the possible exception of sabotage, we do not consider the simultaneous leakage of more than one container to be credible. If massive multicontainer leakage were a major concern, then the entire concept of centralized storage would not be prudent, since this would constitute a policy of "putting all one's eggs in one basket." For purposes of radiation safety, therefore, the siting criteria that we have selected assume the leakage of 1 MCi of ^{85}Kr over a relatively short period of time. The siting objectives are twofold: first, to assure that in the event of such leakage, no individual at or near the fence line receives a dose in excess of MPC standards and, second, to minimize resultant total population doses.

MAXIMUM ACCIDENT DOSES

To evaluate fence-line dose criteria, we have calculated the total leakage required to exceed maximum permissible dose criteria for both accident and routine conditions, conservatively assuming a dilution factor (χ/Q) of 10^{-6} sec/m^3 between the point of release and the fence line. The results of these calculations are given in Table 3. From these data we conclude that even for routine release conditions one may release as much as 45 MCi without exceeding the 3 rem skin dose at the fence line. Therefore, our assumed maximum container capacity of 1 MCi appears to be well within these limits.

POPULATION DOSE CONSIDERATIONS

Our second radiation safety criterion is that in the event of leakage, total population dose (man-rem) will be minimized. With this objective in mind, geographic siting becomes critical. A number of factors, all of which are to some extent interrelated, determine the type of storage site that will minimize population dose in the event of an accidental release. These are:

1. Meteorology

   Meteorology — or, more precisely, the diffusion climatology of the area surrounding the storage site — determines the rate of dilution and the resultant effluent concentrations as a function of time and distance from the release site. Rapid diffusion accompanied by lower individual doses is favored by those locations experiencing a combination of the following factors:

   (a) Strong surface winds, relatively variable in direction.

   (b) Strong daytime heating resulting in neutral or unstable temperature lapse rates.

   (c) A relative absence of night-time temperature inversions.

   (d) A site that is elevated with respect to surrounding locations.

2. Geography

   Geographic factors that would tend to affect potential population dose are:

   (a) The distribution of population with respect to the storage site.

   (b) Topographical features that would affect the rate of dilution of effluents prior to their arrival at population centers.

POTENTIAL SITES

From these considerations we have chosen to consider five hypothetical storage sites within the jurisdiction of the United States. These sites are evaluated on the assumption that a 1 MCi release of ^{85}Kr occurs over a period of a few days or less. It is further assumed that the release occurs at a time when the surface wind direction is the most probable one for that particular site. The hypothetical sites selected for evaluation are:

1. A Remote Island Site

   Because of its relatively low population and distance from any major population center, Johnston Island, southwest of Hawaii, was chosen as a hypothetical site. The Marshall Islands, over 1000 km distant, are the most likely point of first exposure, since surface winds in this area blow consistently towards the west. In our analysis we assume that before reaching the Marshall Islands, the plume of ^{85}Kr would loop into the middle-latitude westerlies and then move toward the east.

2. A Coastal Site

Cape Hatteras, North Carolina has been selected as a hypothetical site since the prevailing winds at this location are usually offshore, but are not as directionally persistent as those at Johnston Island. Although our primary evaluation is based on most probable meteorological conditions, we have in this case also performed a calculation assuming onshore winds.

3. A Remote Desert Inland Site

The Fort Irwin Military Reservation in the Mojave Desert of California was selected as a hypothetical site in this category. There are no population centers within 150 km in all directions. The average winds are toward Nevada; a "worst case" would occur with winds toward Los Angeles. Dose estimates are presented for both cases.

4. A Mountain Top Site

Mt. Whitney, California was selected as a hypothetical site in this category. We have assumed that an all-weather road could be built to the summit and that the storage facility could be sited there at an elevation of approximately 4400 m. The advantage of an elevated site, of course, is that it would allow for maximum turbulent mixing of an effluent plume prior to its arrival at any population center. Average and "worst case" winds are similar to those for the Mojave Desert, due to their proximity. Both cases have been included in dose calculations.

5. A Metropolitan Site

Although it is not considered credible that the storage facility would actually be located within a major population center, we shall evaluate such a site to determine an upper limit to man-rem estimates. For this purpose, an analysis has been performed for a facility located in downtown Chicago, Illinois.

CALCULATIONS

The hypothetical sites and their prevailing wind directions are shown in Fig. 5. The calculational model used to determine population dose was developed by Knox and Peterson (1972). The model has been adapted for use in this study according to the following assumptions:

1. The release occurs at an elevation of 10 m above ground.
2. The effluent stream is eventually dispersed over the entire troposphere of the Northern Hemisphere with a depth of about 15 km. (The model used is applicable only to a hemisphere). Since the Northern Hemisphere contains about 90% of the world population, the calculated population doses will therefore be conservatively large. Population statistics were obtained from 1970 census figures.

Calculation of doses within 1000 km followed the method of Knox (1971) in which functional relationships with distance were developed, except that winds were sector-averaged over 22.5 degrees. The close-in equation for man-rem, D_p, is

$$D_p = \int_0^{\pi/8} \int_{r_0}^{r} D_o\, R(r)\, p r dr d\theta,$$

where

D_o = individual dose at r_o (1 km), rem,

$R(r)$ = ratio of dilution factors at r to r_o, expressed as functional ratios [see Knox (1971) for full discussion],

p = population density, people/km,

r = distance downwind, km,

r_o = distance to site boundary, km, and

θ = azimuthal angle, radians.

Values of R(r) and population density used in this analysis are shown in Table 4.

Beyond 1000 km, Knox et al. (1972) developed an intermediate-range solution. It is assumed that the ^{85}Kr effluent is transported at 40 km/hr, spreading throughout the troposphere horizontally at a rate of 220 km/day (half-width) for the first few days and then at a rate proportional to $t^{1/2}$. If D_o is the site boundary dose, then the total dose is

$$D_i = D_o \left(\frac{D_i}{D_o}\right)^1 \left(1 + e^{-\lambda} + e^{-2\lambda} + \ldots\ldots + e^{-n\lambda}\right)$$

$$= D_o \left(\frac{D_i}{D_o}\right)^1 \quad (15.5),$$

where

$\left(\frac{D_i}{D_o}\right)^1$ is the first-year individual dose.

Table 5 provides summary values of population doses to 1,000 km and for three continents. Long-range Northern Hemisphere population doses out to infinite time are also given. These calculations assume a uniform mass concentration of ^{85}Kr in the atmosphere and a mean residence time of 15.5 yr.

It is apparent that the worldwide population dose is rather insensitive to storage site. The largest Northern Hemisphere dose (for a Chicago location) is about 1-1/3 times the smallest dose (for a remote island site). The only important siting criterion appears to be the avoidance of a location where a large number of people residing nearby might receive large individual doses.

SUMMARY AND CONCLUSIONS

1. Cost-benefit analysis indicates that it would be prudent policy to require the prevention of ^{85}Kr release from fuel reprocessing plants at the present time, assuming this can be accomplished at a cost amounting to less than $1.00/Ci.

2. We have discussed options for accomplishment of ^{85}Kr release prevention from fuel reprocessing plants. No value judgments have been attempted in evaluating these options. However, it has been assumed that a policy of concentrating effluent noble gases, retaining them in pressurized storage tanks, and storing them for long periods at some centralized facility will be adopted. Such a policy would appear to be consistent with current AEC policy on high-level waste management.

3. Criteria for siting a long-term noble gas storage facility should include assurance that in the event of a containment failure:

(a) Maximum permissible dose guidelines (0.5 rem/yr for whole body and 3.0 rem/yr for skin) are not exceeded.

(b) Resultant population doses (man-rem) are minimized.

4. Five hypothetical sites have been evaluated to estimate population doses in the event of leakage. From this analysis it appears that geographic siting may be considered relatively unimportant.

5. Site selection should be based on cost-benefit studies considering:

(a) Transportation and handling costs.

(b) Maintenance and surveillance costs.

(c) Resultant health benefits derived in terms of potential population dose averted.

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Table 1. ^{85}Kr exposure data.

	Whole body	Skin	Units
Concentration - dose conversion factor	1.4×10^{4}	2.1×10^{6}	$\frac{\text{rem-m}^3}{\text{Ci-yr}}$
Total individual dose due to atmospheric ^{85}Kr	5.2×10^{-14}	7.8×10^{-12}	rem/Ci
Total population dose due to atmospheric ^{85}Kr (world population = 3.5×10^{9})	1.8×10^{-4}	0.027	man-rem/Ci
Maximum permissible dose	0.5	3.0	rem/yr
Cost of biological damage	250.	40.	\$/man-rem
Estimated biological damage cost per unit release	0.05	1.00	\$/Ci

Assumptions:

1. Instantaneous uniform atmospheric mixing
2. Atm Vol = 4.2×10^{18} m^3
3. World population (1970) = 3.5×10^{9}
4. Mean atm residence time (^{85}Kr) = 15.5 yr

Table 2. Cost-benefit analysis.

1. Estimated cost for ^{85}Kr extraction and storage:

$$\$0.04\ /\mathrm{Ci}$$

2. Estimated benefit due to ^{85}Kr release averted:

$$\$1.00\ /\mathrm{Ci}$$

3. Benefit/cost ratio:

$$\frac{1.00}{0.04} = 25$$

4. Cost effectiveness for exposure prevention:

For whole body:

$$\$0.04\ /\mathrm{Ci} \times \frac{1}{1.8 \times 10^{-4}}\ \mathrm{Ci/man\text{-}rem} \simeq \$220\ /\mathrm{man\text{-}rem\ averted}$$

For skin:

$$\$0.04\ /\mathrm{Ci} \times \frac{1}{0.027}\ \mathrm{Ci/man\text{-}rem} \simeq \$1.50\ /\mathrm{man\text{-}rem\ averted}$$

Table 3. ^{85}Kr accidental release.[a]

Maximum allowable "fenceline" dose	Maximum allowable container capacity (10^6 Ci) - (assume *fenceline* $\frac{\chi}{Q} = 10^{-6}$ *sec/m*^{3}
25 rem (whole body)	56,000.
0.5 rem (whole body)	1,100.
150 rem (skin)	2,250.
5 rem (skin)	45.

[a] Assume the entire contents of one container is released.

Table 4. Population densities and functional relationships R(r) for calculating population doses to 1000 km.

		1970 population density (people/km^2)							
		Island	Coast		Desert		Mountain		City
Distance (km)	R(r)	Most probable	Most probable	Worst case	Most probable	Worst case	Most probable	Worst case	Most probable
1 - 3	1	0	0	7	5	5	0	0	2500
3-10	$(3r_o/r)^2$	0	0	7	5	5	0	0	2500
10-20	$(3r_o/r)^2$	0	0	7	10	10	0	0	2200
20-100	$0.4\ r_o/r$	0	0	20	15	25	15	25	800
100-1000	$0.4\ r_o/r$	0	0	70	50	200	40	200	70

Table 5. Population whole body doses for a 1 MCi release of ^{85}Kr.

Distance or Continent	Population whose body dose (man-rem)							
	Johnston Is.	Cape Hatteras		Mojave Desert		Mt Whitney		Chicago
	Most probable	Most probable	Worst case	Most probable	Worst case	Most probable	Worst case	Most probable
1 to 1000 km	0	0	45	31	120	26	120	210
North America	40	40	40	40	40	40	40	40
Europe	92	92	92	92	92	92	92	92
Asia	460	460	460	460	460	460	460	460
Northern Hemisphere total	590	590	637	623	712	618	712	802

FIGURE CAPTIONS

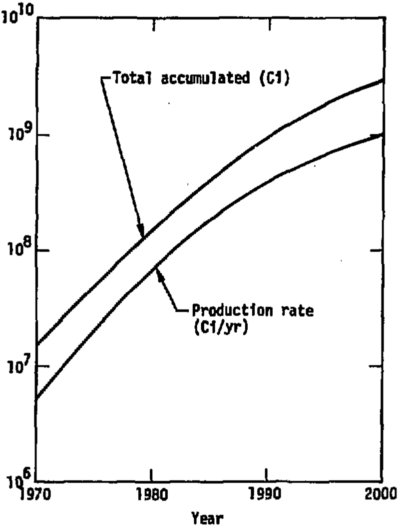
Fig. 1. Projected worldwide ^{85}Kr production. Data from Ref. 1.

Fig. 2. Projected worldwide individual dose due to atmospheric ^{85}Kr.

Fig. 3. Projected worldwide population dose due to atmospheric ^{85}Kr.

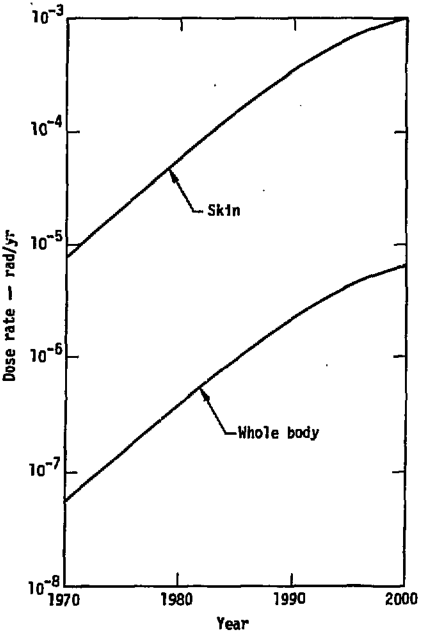
Fig. 4. ^{85}Kr treatment options.

Fig. 5. Potential storage sites; arrows indicate prevailing wind directions.



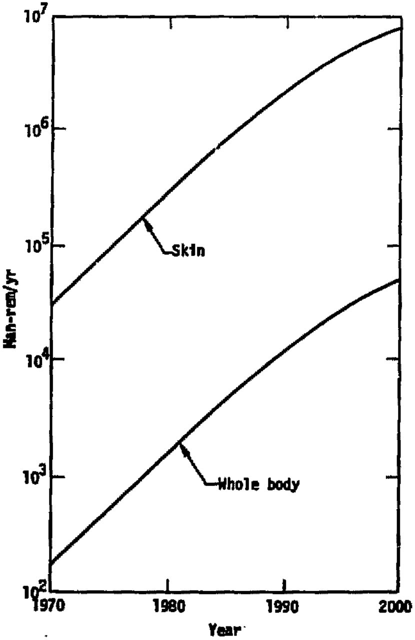
10^{10}
10^9
10^8
10^7
10^6
Total accumulated (Ci)
Production rate
(Ci/yr)
1970
1980
1990
2000
Year

Cohen - Fig. 1



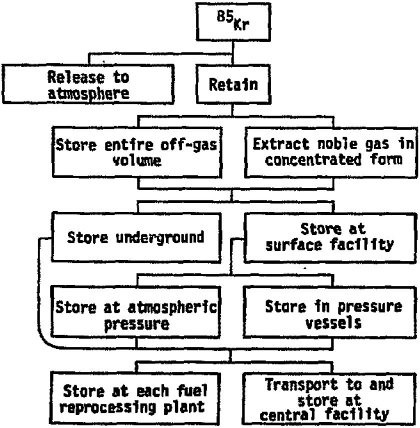
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
Dose rate — rad/yr
Skin
Whole body
1970
1980
1990
2000
Year

Cohen - Fig. 2



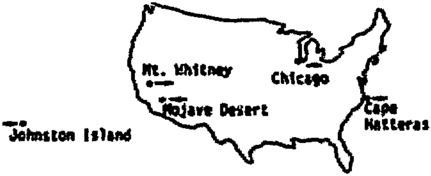
10^7
10^6
10^5
10^4
10^3
10^2
Man-rem/yr
Skin
Whole body
1970
1980
1990
2000
Year

Cohen - Fig. 3



^{85}Kr
Release to atmosphere
Retain
Store entire off-gas volume
Extract noble gas in concentrated form
Store underground
Store at surface facility
Store at atmospheric pressure
Store in pressure vessels
Store at each fuel reprocessing plant
Transport to and store at central facility

Cohen - Fig. 4


Mt. Whitney
Chicago
Mojave Desert
Cape Hatteras
Johnston Island

Cohen - Fig. 5