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DISPOSAL OF RADIOACTIVE WASTE MATERIAL IN THE ICE CAPS OF THE WORLD

P. Philberth

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CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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AUTHOR: P. Philberth

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DISPOSAL OF RADIOACTIVE WASTE MATERIAL IN THE ICE CAPS OF THE WORLD

[Translation of a paper presented by P. Philberth at the Colloquium of the Hydrobiological Commission and the Glacier Commission of 22 January 1960, in Schweizerische Zeitschrift fUr Hydrologie, 23 fasc.1, 1961 pp 263-284]

The exploitation of atomic energy by splitting of heavy nuclei is clearly irresistible, and practically it is hardly unavoidable.

The abrupt rise of the world population requires tremendous expansion of world energy recovery, and we will soon be unable to meet this requirement with water power and coal or oil, especially since coal and oil are important basic materials of the chemical industry. With its synthetic products, the latter will make more and more agricultural areas available for food production and increase the output. It is therefore necessary to fall back on nuclear energy. It is calculated that by 1980 there will be about 10^{11} watts, and in 2000 about 10^{12} watts in world nuclear output.

Since thermonuclear fusion and conversion of the lightest atoms such as hydrogen and lithium are not practicable at present, and large industry exploitability cannot be anticipated for several decades, for a rather long period there remains only the utilization of nuclear energy by fission of the heaviest atomic nuclei by neutron bombardment. Such nuclei are primarily U^{235} which is present in natural uranium up to 0.7 percent, and also Pu^{239} and U^{233}, obtained from normal U^{238} and Th^{232} by neutron addition.

When a neutron impinges on such a U nucleus, the latter is split into two fission products whereby another 2 or 3 fission neutrons are liberated, which continue the chain reaction. The two fission products are driven apart at high velocity, so that within the uranium substance they collide

with other particles and convert this kinetic energy to heat. With such fission, powerful energy of about 180 Mev is liberated. This corresponds to approximately the combustion energy of the millionfold quantity of oil.

The actual problem derives from the fission products that ultimately remain as waste. Because the heavy uranium nuclei have a percentual higher neutron excess than the stable atomic nuclei of medium atomic weight, these fission products have an unallowably high number of neutrons as far as stability is concerned, so that these fission isotopes have high radioactivity. Fission does not always proceed in the same way, so that on the whole there is a great multiplicity of different isotopes. The various isotopes occur in very different amounts, accumulating at about atomic weights 84 to 104 on the one hand and from 130 to 150 on the other. Neutron radiations no longer occur, in just a few minutes after fission. The few α radiators that are present have a half life between 10^{11} and 10^{17} years, so that practically they occur like completely stable isotopes. The decay activity, i.e. the activity of these fission isotopes, extends exclusively to the β and gamma radiation. These various fission radioisotopes have very different energies and half life periods, and their chemical behavior is very different.

Two kinds of harmful effect from such radioisotopes are basically to be distinguished: first through the radiation occurring from the radio isotopes stored in the environment, hence with permanent sources of radiation; secondly, through the scattering of radioisotopes, hence migration of the source of radiation itself.

The first direct radiation involves a hazard only at the moment of emission, and it remains limited to the range of this emission. It concerns only personnel who handle such radioisotopes. These individuals must and can immediately protect themselves by appropriate shielding or spatial separation from the source. Primarily with respect to the transport there are grave and difficult problems, but in no case is there danger here for a large group of individuals or for the world population as a whole. This kind of hazard from immediate radiation is therefore like the effect of bullets from a military firing range, which lose their dangerous properties right after firing and constitute no threat outside the range of the riflemen.

The second case of scattering of radioisotopes in the general circulation of material is quite a different story. Each individual radioactive nucleus behaves outwardly up to the moment of its disintegration like an ordinary nucleus, which is to say without radiation. Only at the moment of its disintegration does it emit a β electron or a gamma quantum, whereby the nucleus of the radioisotope is converted into another, generally stable atomic nucleus. If radioisotopes reach the atmosphere before their disintegration, or open waters or arable land, they will sooner or later be spread over the whole earth and penetrate the living space of every human being. There is quite special danger in the fact that these scattered isotopes are taken up by the organism like ordinary stable atoms and are utilized in building the skeletal structure and the various organs.

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Every single human being and all life is thus involved in such scattering, in most intimate contact with these radioisotopes and their emissions.

Every radioactive nucleus is thus like a loaded cartridge with charge, casing and self igniting powder that sooner or later will eject the ball from the casing. The scattering of radioisotopes is like a mixture of such cartridges among ordinary commercial products, sooner or later getting into all households and all pockets.

The danger of the different radioisotopes depends primarily upon the physical half life, and in addition upon the quantity, together with isotope decay energy and type of radiation, as well as upon chemical and biological properties of the molecules formed by them, and finally upon the degree of spatial distribution after such inclusion.

When an individual atom of a radioisotope disintegrates is entirely undetermined, but it is subject as a whole to a statistical law by virtue of the characteristic half life. Of an original number of atomic nuclei of a radioisotope, after a single half life period, have have disintegrated and half still remain whole: after two half life periods, of the remaining half there again are half that have disintegrated, and ¼ remain: after three half life periods, still 1/8 remain, and after ten half life periods, there is still 1/1024, in other words about 10^{-3}.

From this it appears that isotopes with very short half life develop a very high activity at first, with disintegration of the individual nuclei strongly concentrated in the initial period. After a short while however, they have practically all disintegrated, and they undergo no further scattering and thereby they are no hazard to the general public. Isotopes with extremely long half life on the other hand hardly taper off in their activity, since the decay of the individual atomic nuclei goes on over a long period. For the same reason their activity is so low, however, that they do not constitute a hazard. Danger threatens only from isotopes with half life that on the one hand is so long that in case of scattering they can be entrained over the earth as active nuclei, but that on the other hand is so short that with high probability the isotopes will disintegrate within the lifetime of man. These are isotopes with a half life between about 10^{-1} year and 10^{7} years. Table 1 shows a compilation of all such isotopes that occur in nuclear fission with a half life T in years, with maximum radiation energy in Mev, the percentage occurrence in % calculated on the number of fissioned U atom nuclei and with the annually occurring amount in t in case of an anticipated electric output of 10^{11} W for 1980. The extrapolated half life T_{ex} in years for daughter isotopes, in brackets, is the half life extrapolated on the moment of fission, hence of daughter together with parent.

Table 1.

Isotope	$T(T_{ex})$ a	E MeV	P %	$M(10^{11}$ W) t/a
A few isotopes	$> 10^{10}$	-	-	-
I 129 βγ	1.7×10^{7}	0.19	0.9	0.87
Pd 107 β	7×10^{6}	0.04	0.19	0.15
Cs 135 β	2×10^{6}	0.21	6.41	6.49
Zr 93 β	9×10^{5}	0.06	6.45	4.5
Tc 99 β	2×10^{5}	0.29	6.1	4.53
Sn 126 β	$< 10^{5}$	-	Very little	
Se 79 β	7×10^{4}	0.16	0.056	0.033
Sm 151 βγ	80	0.076	0.45	0.051
Cs 137 βγ	30	1.18	6.15	6.32
Y 90 β 2.7 d	(28)	2.27	5.77	3.90
Sr 90 β (Y 90)	28	0.54	5.77	3.90
Kr 85 βγ	10.4	0.67	0.29	0.19
Vd 113 β isomeric state	5.1	0.58	Very little	
Sn 121 βγ	5.0	0.42	0.015	0.014
Pm 147 βγ	2.7	0.22	2.4	2.65
Sb 125 βγ	2.0	0.64	0.021	0.02
Eu 155 βγ	1.7	0.25	0.03	0.035
Rh 106 βγ short	(1.0)	3.5	0.38	0.30
Ru 106 β (Rh 106)	1.0	0.04	0.38	0.30
Pr 144 βγ short	(0.78)	3.0	5.67	6.13
Ce 144 βγ (Pr 144)	0.78	0.31	6.0	6.5
Sn 119 $e^{-}\gamma$ isomeric state	0.67	0.065	Very little	
Sn 123 βγ	0.36	1.42	0.0013	0.001
Te 126 βγ	0.30	0.66	0.035	0.033
Nb 95 βγ 0.1 a	(0.27)	0.98	6.25	4.45
Zr 95 βγ (Nb 95)	0.18	0.89	6.25	4.45
Y 91 βγ	0.16	1.54	5.4	3.68
Sr 89 β	0.14	0.46	4.79	3.20
Cd 115 βγ	0.12	0.63	0.0007	0.0006
Te 129 β	0.11	1.5	0.35	0.34
Ru 103 βγ	0.11	0.7	3.0	2.32
Ce 141 βγ	0.09	0.6	6.0	6.35
Many isotopes	< 0.05	-	-	-

Enclosure for 10 half life periods gives a not yet sufficient drop in activity to 10^{-3}, so far as disposal is concerned. Enclosure for 20 half life periods gives an activity drop to 10^{-6} which ought to be adequate in infrequently occurring chemically and biologically noncritical isotopes, and in the case of isotopes with long half life, as well as in pronounced spatial dilution after the end of the enclosure. An enclosure for 30 half life periods gives a satisfactory drop in activity to 10^{-9} for most isotopes. Enclosure for 40 half life periods gives an activity drop to 10^{-12} which ought to be sufficient even for frequently occurring isotopes that are extremely critical both biologically and chemically, and for isotopes with shoft half life and also with remaining heavy spatial concentrations after the period of enclosure. An enclosure of 50 half life periods give the practically complete drop in activity to 10^{-15}.

If it could be agreed upon to undertake chemical decomposition of fuel elements only 1, 2 or 3 years after leaving the reactor, isotopes with half life periods of 0.05 years or less would be almost completely disintegrated inside the compact metallic bodies of the fuel elements. Longer storage before chemical decomposition would be hard to tolerate. The safety problem with increasing half life period quickly gets more critical. The maximum threat is in the case of Sr^{90} together with the shortlived daughter Y^{90} and in Cs^{137}. These combine the most unfavorable half life of about 30 years with large quantitative occurrence (about 1700 t Ra equivalents annually at 10^{11} watts) with highly energy-rich radiation and high biological effect. In the interest of the future of mankind and for prevention of severe physical and psychic damage, this requires the elimination of these substances with the hardly conceivable reliability of 10^{-6} to 10^{-8}. This makes an absolute enclosure time of no less than 1000 years a requirement, while 1500 years could mean ample security. Another very critical isotope at the bottom of the scale is Kr^{85} which it is true has only a 10 year half life and occurs in small amounts with low radiation energy, but it requires special techniques as a noble gas. It is adsorbed at the lowest possible temperatures on activated charcoal and stored under complete seal. At the top of the scale we have Sm^{151} which also occurs in very small quantities and with low radiation energy, and as a rare earth forms an insoluble oxide, but because of its 80 year half life it nevertheless requires safe enclosure for about 1500 years.

As a gift of the Creator to mankind in need of atomic energy, there is the circumstance to be considered that among the fission isotopes, there is a gap between Sm^{151} with its 80 year half life and the next in succession Se^{79} with its half life of 70,000 years, namely a gap of three whole tenth powers, whereas the half life of isotopes above and below are close together. Se^{79} and Sn^{126} seldom occur, with low radiation energy and slight biological effect. Moreover there is no gamma radiation, except in long lived I^{129} which is rather rare and radiates with low energy. Together with these circumstances, the half life periods of these isotopes are already so long that the activity that develops can be regarded as harmless. The total amount of these long lived isotopes evenly distributed in the sea would cause additional sea activity that would be less by several orders of magnitude than natural sea activity (K^{40} and Rb^{87}). Above I^{129} there

follows after another long gap of three tenth powers other isotopes with extremely long half life periods of more than 10^{10} years, which are not of any importance.

Therefore. The highly active fission isotopes with short half life disintegrate too swiftly to give occasion for scattering. With respect to the dangerous isotopes with medium half life periods, a scattering of a maximum of $1:10^{-6}$ to $1:10^{-3}$ must be guaranteed during enclosure times of 1500 years. Less than 1000 years would not be allowable. More than 2000 would be unnecessary. With respect to the few active fission isotopes with long half life periods it is only necessary to deliver the isotopes to the general material circulation -- especially the oceans -- so slowly that no local concentrations can build up. The fission isotopes with extremely long half life periods present no more dangerous activity. A disposal method must meet these requirements.

As opposed to the "half life period" T working on the basis $\frac{1}{2}$, the average life duration works on the basis I/e: the average life duration is thus with like dimension greater by the factor I/In 2 1.44 than the half life period. In our dimensioning with T in years (a) and in seconds (s) we have $\tau = 45.5 \cdot 10^6$ T.

The reactor waste disposal process is broken down on the one hand into the problem of the place of disposal, where the fission isotopes are permanently to be kept, and on the other hand into the problem of transportation of the isotopes from the chemical decomposition of the fuel element to the final storage at the place of disposal. Transportation may harbor special, possibly even practically the only difficulties of the disposal problem. However the risk associated with transportation is different in principle, and much simpler, than the risk entailed in the place of disposal.

Current deficiencies of a method of transportation show up immediately. The accident figure of a transportation method has its effect on occurrence of the first accident. Immediately upon appearance of such deficiencies, they can be dealt with or possibly the method can be changed. Here previous experience and current technical developments would be usable. Transportation deficiencies thus concern basically only the small quantities, comparatively, of material in transit.

In crude contrast to this are the inadequacies arising with respect to the place of disposal. In the slowness of marine, geological and glaciological processes and the persistent steadiness of diffusion processes, it would hardly be possible to determine the deficiencies of a disposal place before some years or decades, in observation of slowly beginning scatter. A scattering would then practically inevitably progress. Deficiencies in the place of disposal would thus extend to accumulations built up over years and decades, so that the risk involved in the matter of the place of disposal would be more serious by whole orders of magnitude than the transportation risk.

Absolute safety at the place of disposal is practically alone essential and decisive for planning a disposal system. Transportation problems with their temporary risk could then be decisive only if they were considered to be insurmountable. With the multifacetted technical possibilities and rapid development, it should be assumed that the transportation problem is in principle capable of solution, in disposal on earth. Only in the rather utopian disposal of reactor wastes away from the planet would transportation present serious difficulties. Not only would the danger of accident be much too high, but it would entail more consumption for the heating of necessary amounts of propellants in conventional power plants.

How do we stand now in the face of safe deposition on earth that is decisive for the whole waste problem ?

Safety at the place of disposal is determined essentially by the activities, with corresponding mass and heat development, that must be eliminated (table 2).

The actual fission isotopes have practically the same weight as the fissioned uranium. Since the pure fission products, because of their high activity, are heated far above their temperature of vaporization, they are handily diluted, so that the mass is correspondingly greater. Wastes with specific activities of less than 0.1 curie/g to more than 10 curie/g are manageable. An activity of 1 curie/g which by definition is the same as the activity of 1 g Ra is already to be regarded as high activity that no longer allows accumulations by the ton.

Waste heat development is of course only 1/1000 of reactor output and for this reason it can no longer be utilized. Since however at a later time a substantial part of the world energy requirements will be supplied by nuclear fission, even the waste heat assumes a stupendous value. If we assume no expanded use of nuclear energy -- with 10^{11} to 10^{12} watts we can consider that a certain saturation has been reached -- then continuous nuclear fission with no time limitation and constant output would give rise to still more waste activities and quantities of heat. Since however a constant disintegration of previously occurring active nuclei would proceed, after a long time an equilibrium in the total waste would be established, between new accretions and continuous disintegrations. We would have to count on a future equilibrium activity of about 10^{12} curie -- corresponding to 1,000,000 t Ra -- and a heat balance of about 10^{9} cal/s -- corresponding to terrestrial heat of 100,000 km^2 of the earth's surface.

We immediately perceive that avoidance of actual disposal by storage as liquid waste in multiwalled tanks is no solution in the long run, but merely postpones the problem. The quantities increase in orders of magnitude like the volume behind a valley dam, so that objectionable temperature increases are hardly to be prevented. The isotopes with medium half life would make storage for generations necessary. Right now the US is storing about 10^{5} t highly active liquid waste in tanks. It should by no means be

Table 2.

Uranium and fission isotopes			
Year	*Reactor output thermal cal/s electric W*	*Fissioned uranium = fission isotope t/a*	*Operating uranium t with 2.5 yrs prestorage*
1955	10^9	2	10^3
1965	10^{10}	20	10^4
1980	10^{11}	200	10^5
2000	10^{12}	2000	10^6
24% efficiency (elec/therm)			

Waste: with 1 curie/g and 2.5 years prestorage (with 0.1 curie/g in immediate disposal)		
Year	*Currently occurring activity curie/a*	*Currently occurring mass t/a*
1955	10^8 (10^9)	10^2 (10^4)
1965	10^9 (10^{10})	10^3 (10^5)
1980	10^{10} (10^{11})	10^4 (10^6)
2000	10^{11} (10^{12})	10^5 (10^7)
Waste activity/useful energy:	8 Curie/MWh	(80 Curie/MWh)
Waste mass/useful energy:	8 g/MWh	(800 g/MWh)

Equilibrium of total waste with 2.5 years prestorage (with immediate disposal)		
Permanent electri useful output W	*Equilibrium activity curie*	*Equilibrium heat development, cal/s*
10^{11}	10^{11} (4×10^{11})	10^8 (5×10^8)
10^{12}	10^{12} (4×10^{12})	10^9 (5×10^9)
1 Curie = 3.68×10^{10} events of disintegration/s		

Average uranium burning duration = ½ year

overlooked, that in case of catastrophe there could be a general contamination caused by such tanks that would be comparable to the contamination by nuclear war.

For further utilization of atomic energy there remains only the possibility of drawing on natural broad areas of the earth for waste disposal. These methods can be divided into three main categories: water, land and ice.

The chief difficulties in disposal in the water reside in the property of water as a thin fluid excellent solvent with a high dipole moment and high dielectric constant and supplementary valence. In the oceans, the effect of motion of the sea and salt water on receptacles and glass masses can hardly be estimated. The ocean currents together with marine organisms must be assumed to effect scattering in a way that at present is not subject to check. In view of the strong heat development of reactor wastes we would have to count on occurrence of strong heat convection which would be in addition to that of the ocean currents and might affect them. Especially, disposal in oceanic sedimentary pockets would not basically eliminate the difficulty. We are not clear at present on how glassed-in waste will act in the long run when sunk in large freshwater lakes.

The main difficulties in disposal on land reside in the solid particulate structure, of finest porosity, and the constant danger of cracks from seismic disturbances. The effect of air pressure fluctuations and ground water movements is critical then. Particularly unpleasant is the heat development of nuclear wastes, whose heat stagnation makes it practically impossible to sink large quantities to great depths, and makes it extraordinarily difficult to add further waste. Moreover it is very wrong if large areas would in this way be lost for future settlement that might be possible through future technology or necessary because of overpopulation. To what extent especially the use of arid high mountain basins in South America or the pumping in as liquid waste into subterranean salt deposits or placing in domes of salt mines may basically be suitable cannot be judged at the present time. In any case, these possibilities depend too much on local conditions, and they would not at all suffice for handling future quantities.

At the conference on disposal of radioactive waste held in November 1959 in Monaco, the IAEA director general, Mr. Sterling Cole (US) correctly pointed out that the method of reactor waste disposal in any country also concerns the welfare of all other nations. Every nation thus has to solve its own waste disposal problem satisfactorily but it ought -- so far as possible and to the extent that opportunity offers -- also to hold proposed solutions in mind for other countries, and promote them. Such cooperation is not only necessary for all nations with respect to emergency, but it could be the way to agreement that is much harder to reach by other routes in matters of interest in nuclear activity. The emergency is shown in a frightening way when we consider that at this international conference of specialists no universally satisfactory method for disposal in water or on land could be arrived at. It is worth noting in this connection that this was not at all possible on the basis of quantities at that time, and the future much greater quantities could not even be considered for this reason. We find ourselves therefore confronted by a very dismal situation in waste

disposal. The indication that future use of nuclear energy apparently will not be as much as was anticipated earlier, and that sooner or later the fusion process will be perfected does not make the problem a bit easier. Not only are reactor wastes shockingly large right now (just one plutonium bomb produces 20 times in reactor waste activity in the course of its manufacture than any subsequent detonation with its cloud would release) and not only is fusion at least two to four decades away, but quite basically it does not seem defensible to let prevention of worldwide contamination depend upon questionable future expectations. The present situation requires that in all countries all methods that come into question in any way whatsoever be examined with greatest care.

For this reason it was welcomed at the Monaco conference that a newly proposed method was reported that at least promises to solve the problem of the place of disposal for future waste. This is reactor waste disposal in the earth's ice caps.

The comparatively thin floating masses of ice at the North Pole or the comparatively small and quickly moved ice masses of glaciers are not suitable for disposal of radioactive wastes. In the Antarctic, in Greenland and possibly in Iceland however there are suitable icecaps over solid ground, in enormous areas and thicknesses, with a practically stationary zone at the center. The ice area of Antarctica is 14,000,000 km^2. That of Greenland is 2,000,000 km^2. The maximum thickness of the ice of the Antarctic is 4 km. That of Greenland is 3 km. It is proposed that radioactive wastes be brought into the central zone above the firn [névé] boundary of this ice cap, right under the surface of the ice.

More detailed investigations show that just those properties of the ice itself and of these icecaps that originally aroused misgivings are specially suitable for the waste problem. Ice has neither the flowing movement of water nor the crystalline hardness of stone. Ice has a mechanical consistency that corresponds to the transition between a highly viscous fluid to a plastic solid.

The viscosity of ice is so high on the one hand that no convection occurs, and the ice movements in the interior of the icecaps are sufficiently slow for the waste problem. Ice's property, similar to that of water, of adding and accepting atoms and molecules, leads on this account right to a better fixation of the waste substances at the place of disposal. Even with substance stored freely in the ice. The viscosity of ice is moreover so high that receptacles barely sink with reference to the surrounding ice mass, at the most a few mm per year, which would be regarded as insignificant for the waste problem. Heat development would not be so strong anyway as to melt the receptacles in. This was achieved with 20 kg receptacles with a specific activity of no more than 1 curie/g: with 400 kg receptacles with 0.1 curie/g. By special configurations, even with significantly higher specific activities, melting in would be avoided.

The plasticity of ice on the other hand is again so high that even the pressure of an ice layer several meters thick in the central zone is sufficient to let cracks flow back together in a short time, to form a compact mass.

Ice thus practically combines an an almost ideal way the dense closing off of a liquid layer with the immobility of a solid. Thus mechanical damage to the waste containers and of the structure of the ice mass by seismic shock imply practically no source of danger.

The surface of the icecaps, in the central zone, is substantially above the firn line, with average annual temperatures of -50° C in the Antarctic and -27° C in Greenland. Even in the hottest time of the year, the melting point of ice is not reached. Liquid water which is the most dangerous scatterer of radioisotopes thus does not occur at all. In the central region of Antarctica the temperature maximum is always significantly below the melting point whereas in a few hot summers in Greenland it may briefly exceed the melting point. The scant superficial melt water in the central zone is sucked up by the uppermost centimeters of the firn on the spot, forming fine blue ice layers in the firn. This surface melting at the temperature maximum does not lead to any movement of water in the central zone, and therefore it has no disadvantageous connotations for the waste problem.

Precipitation occurs as snow which in the central zone yields a steady superficial increase in mass so that a given surface is covered over with newer and newer layers. By the pressure that increases with depth, the surface snow is compacted to more and more dense firn, and finally to more or less compact bubble ice. By this constantly new overlayering associated with increasing firn density, the enclosure of reactor wastes deposited at the surface or close below the surface will continuously be reinforced. This gives an uncommonly high degree of safety.

Even a few meters below the surface, the temperature differences between summer and winter precipitation have been balanced so that the average annual temperature prevails. The interval between temperature of the middle of the year and melting temperature, the relatively high heat conductivity of ice and firn, the continuous withdrawal of heat by the cold precipitation, and the enormous areas available in Greenland and in the Antarctic allow the powerful heat development of tremendous future quantities of waste to appear insignificant.

More detailed investigations have led to the following results with reference to:

1. enclosure time in the ice mass
2. outward diffusion of particles arriving free in the ice
3. temperature elevation in the superficial ice layer receiving the waste
4. temperature elevation on the rock base of the ice mass.

Enclosure Time

Because of the precipitation, these ice masses have a continuous superficial growth, whereas at the fringe glaciers there is a corresponding continual ejection of mass into the surrounding sea. There is therefore a slow inner movement of these ice masses in which initially superficial ice places sink down deeper and deeper and migrate to the edge. Enclosure time ends when the edge is reached. In the border area, there is preponderantly a horizontal migratory movement with correspondingly short enclosure time.

In the central region, there is predominantly a vertical sinking movement with correspondingly longer enclosure time. A certain middle position of the central zone has practically only a rate of vertical descent, with theoretically unlimited enclosure time. An estimate of enclosure time t_e gives

$$t_e > \frac{2H}{3N} \ln \frac{r}{r}$$

This gives for the central zone of Greenland, depending upon the position of the apex of the icecap, 10,000 to more than 100,000 years (as Prof. Haefeli explained). With a required enclosure of not even 2000 years for a medium half life period of one of the critical isotopes, this gives an extraordinarily great margin of safety. The waste mass distributed over the whole central region, spread over this enormous period between 10,000 and 100,000 years, will be slowly and successively released to the ocean, so that even for the few critically longlived waste isotopes there will be guarantee of uniform distribution to the seas such as cannot be given by any other method. The enclosure times thus correspond exactly to the ideal conditions.

Outward Diffusion

If over a large area at a certain depth below the surface, particles are liberated, they migrate as the result of diffusion from the place of their release. The measure of displacement is in proportion to the square root of the time. With a given fixed surface therefore, sooner or later all particles will diffuse out over such a surface. This is about what happens with disposal in solid land.

It is quite different here, where there is no fixed surface but rather where the surface at any time is always being covered anew by the current annual precipitation, thereby receiving fresh covering layers. The case is such that the diffusion curve proceeding with the square root of the time lags behind a surface that advances linearly with time, so that the diffusion wave after initial greater speed later falls farther and farther behind the surface. The integral of outward diffusion over all times can thus be kept arbitrarily low if at the time of this overtaking of the diffusion rate by the surface rate, as a consequence of adequate initial placement depth, only a few particles will have found their way to the surface.

Calculation of this outward diffusion gives extraordinarily favorable results: $V \leq e^{-2a/D}$.

Even if the value of the diffusion constants be replaced by values as given in the case of molecules dissolved in liquid water, with a few meters of insertion depth, this outward diffusion comes to 10^{-20} to 10^{-50}. It is therefore absolutely without danger if even all the receptacles were to dump their total contents into the firn.

We see that what otherwise is the most troublesome problem vanishes entirely -- precisely on account of the movement and the precipitation which otherwise were the most feared limitations on safety.

Maximum Temperature Elevation of the Ice Mass

We are concerned to know how strongly the ice temperature would rise from heat development by radioactive waste above the temperature without the waste. This temperature without the waste in the upper layer of the icecap is about the average annual temperature, and it rises because of terrestrial heat toward bedrock. This maximum temperature rise appears in those layers in which the waste is stored, and accordingly migrates downward with the general precipitation-conditioned ice flow. If however the wastes are always disposed near or under the surface, in a disposal period of about 100 years (i.e. with 100 years of use of nuclear fission) this zone of strong temperature elevation expands only to a few hundred meters of the uppermost layers. To estimate the maximum temperature rise, we take not only 100 years during nuclear fission but nuclear fission continuing indefinitely with constant electric output of about 10^{12} watts. Proceeding in time, waste will be ejected with a temporary heat content equal to the equilibrium value of the continuous waste heat development Q in cal/s. This would always be brought to the samd area F of the same central zone at the same depth Z below the surface in question. Since the surface continuously grows because of precipitation, successive wastes are disposed in layers one over the other, whereby the heat development in each layer tapers off with the average life τ ($\tau = 4.5 \cdot 10^6$ T) of its radioisotopes. From the continuous addition of new heat emitting layers and the continuous heat withdrawal by thermal capacity c of the lower-temperatured precipitation and continuous carrying off of heat by the firn thermal conductivity y to the surface, we have the maximum temperature rise as an equilibrium value according to

$$\Delta = \frac{Q}{F}\,\frac{1}{nc}\left\{1-\left[1+\frac{n^2 c\tau}{y}\right]^{-1}\cdot e^{-\frac{Z n c}{y}}\right\}.$$

If we use as waste area F 10^{15} cm^2 (i.e. only 100,000 km^2) of the ice surface, under these conditions, from 10^{12} watts electric output and 2.5 years prior storage, we have a maximum temperature increase of only 2^o C. With immediate disposal, correspondingly 10^o C. The heat balance development of 10^9 cal/s gives on this area exactly the value of terrestrial heat, 10^{-6} cal/s cm^2, or with $5 \cdot 10^9$ cal/s, a multiple of 5 of terrestrial heat.

Temperature increases and heat releases of this kind constitute no problem, of course, and besides this goes on only in the uppermost layers below the surface, with their temperatures that are far below the melting point.

Temperature Elevation at the Rock Base

Slight though the heat development by the waste may be in proportion to natural thermal evolution, the following has to be considered:

Because of terrestrial heat entering the ice mass from the bottom, there is in all cases a temperature gradient with a rise in temperature near the base. Considerations solely in terms of thermal conduction would come to the result that melting temperature will be reached at the base, and there will be a permanent melting away of 2 to 5 mm per annum. Because of the continuing vertical movement of the ice however, there are cold superficial masses moving steadily downward, whose thermal capacity would apparently take up the terrestrial heat completely, according to the Robins theory. In spite of the terrestrial heat, there can be a solidly frozen condition at the base, where it would be to be assumed that the base temperature would be rather near to the melting point.

It has not been cleared up yet, how it actually is. But it is possible that a solid frozen state of the ice masses at the base is a requirement for the existence of the icecaps.

A sliding away of all the earth's icecaps from their bedrock would cause the sea level to rise by about 80 meters, taking over the most fertile low-lying parts of the earth. The high polar rock land that would be laid bare would literally amount to an exchange of bread for stone. Even relatively slight elevations of the base temperature are meticulously to be avoided for this reason.

The rise in the temperature at the base is given as function of time t after a disposal epoch T_B according to:

$$\Delta_B \approx \left[\frac{Q}{F}\,\frac{T_B}{\sqrt{4\pi C \gamma t}}\cdot e^{-\frac{H^2 C}{4\gamma t}} e^{-\frac{2Nt}{H}}\right]\left[e^{-\frac{Nt}{H}}\right]\left[\nu\left[1+\frac{n^2 c_p}{\gamma}\right]^{-1}\cdot c - \frac{2nc}{\gamma}\right]$$

The first factor of the equation concerns the vertical heat flux from heat conduction by the ice and vertical movement of the ice. The second factor relates to the horizontal heat flux from horizontal ice movement. The third factor is heat withdrawal by the thermal capacity of the precipitation and firn heat conduction through the surface.

The base temperature does not reach any limit value but is in proportion to the disposal period which we assume to be 100 years. Under these conditions we still have no elevation of base temperature to about 15,000 years. Then it rises and after 20,000 to 30,000 years it reaches a maximum and then declines again. This maximum temperature increase at the base is substantially less than 0.002°C at $Q = 10^9$ cal/s, which corresponds to a hundred years of nuclear current output of 10^{12} watts with 2.5 years prior storage, or less than 0.01°C with immediate disposal.

We could well assume that such slight increases in base temperatures would in no way constitute a significant influence. Moreover such an influence could be prevented by special measures.

An area of only 100,000 km^2 is taken for these temperature increases in ice mass and bedrock. In Greenland alone, and certainly in the Antarctic there would be much greater areas available. We have again a margin of safety of more than two orders of magnitude.

This would take care of the question of safety at the place of disposal. Although the transportation problem is much subordinate because there is only momentary risk relating to amounts actually in transit, we will consider it briefly.

We cannot consider the transportation problem to be solved for the moment. This would involve technical questions that are beyond my field of competence. For this reason I can only indicate possible approaches and urge further study.

Basically it would be advantageous to use air transport. Here the waste -- solidified, if possible -- would be charged into bomber style containers and simply ejected from medium altitudes on the firn areas of the central zone. Firn density at the surface is only 0.4 that of ice, and it increases steadily downward. This would provide ideal conditions for a clean injection of such container boms to a few meters' depth with comparatively little mechanical stress to the boms. A possibly desirable deeper embedding of the waste, at 20 to 30 meters, would be particularly easy and acceptably managed if with the given specific waste activity the waste mass were to be made so great in a container that melting temperature would be reached at the surface of the container, and it would melt itself in. Since with increasing density at increasing depth, the heat conductivity of the surroundings increases and at the same time the waste activity declines, the depth could be exactly set at which such containers should lodge below the surface. Such specific activity overloading would also lower the transport weight. Waste containers of 0.1 t at a specific activity of 1 curie/g, i.e. with 10^5 curie, would lodge at about a depth of 20 to 30 m: 0.1 curie/g would give a container weight of about 2 t.

This would correspond to an altogether convenient and acceptable technology.

In the matter of transportation costs we have to consider that with a prior storage of 2.5 years there would be only about 8 curie waste activity per MWh electric utility. With immediate disposal there would be about 80 curie/MWh. Deutsche Lufthansa calculated transport costs for this project from central Europe to Greenland at about $500/t according to present technical conditions. Transportation without shielding with 1 curie/g would come to about 0.4 cents per MWh. At the proposed production cost of $12 per MWh, air transportation costs would therefore amount to only one-third per thousand of the other nuclear current production costs.

Transportation without shielding means radiation in space of about 10^7 curie to the load. Unprotected presence would therefore be harmless only at a distance of at least 2 km. The cargo aircraft would therefore have to fly at at least this altitude, either program controlled or remote controlled from accompanying aircraft.

Economically about one percent of the air transport costs could well be absorbed in the total current cost. Therefore the wastes could be shielded with 30 times their weight. This would still not allow piloted flight, but safety distances and technology would be substantially eased. With 16 t carrying capacity (Super Constellation) we have for $5 \cdot 10^5$ curie waste activity at 1 curie/g specific activity and 2.75 g/cm^3 specific waste weight, the possibility of a spherical lead shield with 36 cm wall thickness. With 30 t for 10^6 curie at 1 curie/g and 2.75 g/cm^3, 44 cm Pb. With 16 t for 10^6 curie at 16 curie/g and 2.5 g/cm^3, to cm Pb. We are thus within technologically feasible and economically tolerable ranges for shielded air transport.

If the reactor facilities are so placed that such transportation can be effected solely over the ocean, in case of a crash still only wastes in proportion to the accident figure would reach the ocean, as opposed to general marine disposal. The safety of flying over land could be enhanced by safety parachutes that in case of catastrophe would prevent the containers from being unsheathed. These aspects of air transport should be carefully tested. Disposal in the ice is in no way restricted to air transport.

The other oceanological and geological methods of disposal also entail freighting of the waste. It ought not to be decisive here if such ship cargo would be brought to certain places in the sea or to the Greenland coast. Especially on the southeast flank of Greenland, there are chains of high mountains that have only few inland glaciers. Behind these the inland ice closes almost directly with great height, little crack formation and slight ablation. It would be no great technical problem to drive a slanting tunnel through such a mountain mass from the coast to the ice surface, through which the waste could be taken to the ice surface and towed from there with caterpillar tractors to the central zone. Since with this method there would be less importance attached to saving in bulk, wastes could be immediately shielded and packed for sliding. Here a water jacket shield (instead of lead) could be considered, where the shield would be partly saved on at the bottom. Possibly the whole towed material could simply be left standing on the surface of the central zone, and the other natural processes could take over.

Finally there would also be the possibility of combinations, e.g. transport by ship to a Greenland air field and then air transport to the central zone of the inland ice. Not only the problem of long tracks in uninhabited territory but also the problem of monitored remote control from the bordering mountains have especially favorable conditions here. The extension of a few special machines over short stretches lowers the accident figure and the costs considerably.

Above all in view of the latter possibility I do not believe that the transportation problem, with closer consideration of the multifarious possibilities, will stand as a substantial block. To reach an unobjectionable and final judgment in the problem, much serious work remains to be done. Professor Renaud of Lausanne in his statement of 12 December 1958 in the Gazette de Lausanne issued a call especially to glacier specialists and physicists to engage in thorough study of all the questions related to this problem. I should like to associate myself with this call. Unfortunately far too little attention as been paid to the problem of disposal of radioactive wastes from the national side. When we consider that a defective disposal of waste of reactor radioisotopes can entail general contamination as in atomic war and strike other generations with severe physical and mental hereditary damage, there ought to be official concern with the waste problem equalling the defense efforts. That this does not even remotely happen probably depends on the fact that the whole problem area is entirely novel in human history and the general consciousness has not grasped it. Just as important as clarification of the scientific questions by the work of individual scientists therefore is that scholars use their influence to effect solution of this question by competent public groups of specialists. Because here only peaceful generation of nuclear current is involved, but the military nuclear explosives production even now continuously produces radioactive reactor waste like that anticipated between 1980 and 2000 for nuclear current production, the waste disposal problem is even now of highest urgency.

Comprehensive reports on disposal of reactor waste

[1] Proceedings of the International Conference on the Peaceful Uses of Atomic Energy; Genf 1955 (insbes: Bd. 9; E. GLUECKAUF; W.D. CLAUS).

[2] WASH-742, Status Report on Handling and Disposal of Radioactive Wastes in the AEC Program; US-AEC, August 1957.

[3] Proceedings of the Scientific Conference on the Disposal of Radioactive Wastes; sponsored by the IAEA and UNESCO, Monaco, Nov. 1959 (insbes: J. JOSEPH; PHILBERTH, dazu C.A. MAWSON and V.I. Spitsyn).

[4] B. PHILBERTH; ATOMKERNENERGIE H 11/12 1956 und H 3 1959; Comptes rendus, Academie des Sciences, No. 14, 1959 (Paris).

MAGNITUDES IN THE TABLES

T Half life period in years

(T_{ex} Half life extrapolated on the amount of fission)

E Maximum radiation energy (β or γ) in MeV

P Isotope fraction per 100 fissioned U atom nuclei in %

M Annual occurring quantity of isotopes with 10^{11} W electric output in t/a

Assumed to be Constants

H	ice depth	3×10^5 cm
N	precipitation ice value	3×10^{-7} cm/s
n	precipitation firn value	6×10^{-7} cm/s
C	thermal capacity of the ice	0.45 cal/°C cm^3
c	thermal capacity of the firn	0.25 cal/°C cm^3
Y	thermal conductivity of the ice	4×10^{-3} cal/°C s cm
y	thermal conductivity of the firn	1×10^{-3} cal/°C s cm

D diffusion constant of the particles: for each type of particle to be set in separately, especially high value 10^{-5} cm^2/s

τ average life duration of the isotope: to be set in separately for each kind of isotope average value 10^8 s

Arbitrarily Assumed as Permissible Magnitudes

r/x	Distance relationship of edge of the ice to point of ejection: sometimes from the highest elevation	5
Z	Depth of penetration of the container bombs	2×10^3 cm
Q	Heat content of the waste to be disposed of per time unit at reactor output	10^{12} W 10^9 cal/s
	Maximum temperature elevation of inner ice layers	2°C

Magnitudes Obtained as Results

t_e	Enclosure time of the container bombs	$t_e > 10^{12}$ s (30,000 yrs)
V	Proportion of particle quantities diffusing out through the surface to those arriving free in the ice	$V < 10^{-50}$
F	Area of the ice region to be used for disposal: at 10^{12} W output	$F = 10^{15}$ cm^2 (10^5 km^2)
T_B	Time span of the disposal epoch	$T_B = 3 \times 10^9$ s (100 yrs)
Δ_B	Base temperature elevation as a function of time $t(s)$ after the disposal epoch	$B \leq B_{max} < 0.002$°C

Values Q, Δ, Δ_B apply for 2.5 years prior to storage: with immediate disposal, value multiplied by 5.