THE COST OF NUCLEAR DESALINATION

What would be the cost of fresh water obtained by desalination of sea or brackish water with the help of a nuclear reactor? What methods are being employed for such costing and evaluation?

These are basic questions for the increasing number of countries wich are considering water desalination for the production of drinking water or for industrial or agricultural purposes.

Following the recommendations of a panel of experts convened by the IAEA in Vienna, Austria, in April 1965, the Agency is now preparing a report on the desalination methods used or developed in various countries. Another panel met in Vienna in April of the current year, to help the Agency with the final draft of this report which is due to be published this autumn.

The panel, 20 experts from 7 countries, was chaired consecutively by Mr. N. Carrillo (Mexico) and Mr. V.N. Meckoni (India).

ISOTOPE CHRONOLOGY AND RECORDED HISTORY

By Willard F. Libby

Professor Libby gave a lecture on radiocarbon dating at IAEA headquarters, Vienna, in January 1966.

Nature produces radiocarbon by the irradiation of the air by cosmic rays. Radiocarbon has an average lifetime of 8000 years and a half lifetime of about 5 700 years ; a good part of the radiocarbon in your body was produced before the dawn of history. History is a really very recent matter in terms of radiocarbon. Our oldest historical records are less than one half-life of radiocarbon. In terms of the age of the earth, however, radiocarbon is short-lived. The age of the earth is something like 5 000 million years, which is a million half-lives of radiocarbon. Radiocarbon has little application to the broad sweep of geological processes, but it does have application to human history.

Now this is how it works. In the topmost layers of the atmosphere, at altitudes of about 50 000 feet, cosmic rays produce radiocarbon by converting the nitrogen into carbon 14, with a different chemistry. Carbon in air will burn and the product is mainly carbon dioxide. Carbon dioxide is our substance. We are made of three things in essence - carbon dioxide, water

Dr. Willard Libby, who received the Nobel Prize for Chemistry in 1960 for his work on radiocarbon dating.

vapour, sunlight and a pinch of salt! Photosynthesis produces the green plants by the conversion of carbon dioxide and water to plant materials, by the incorporation of sunlight. Well, as you see, the material from which life grows comes from the air and comes from the carbon dioxide in the air, and in eight thousand years the atmosphere will be very thoroughly mixed by the winds. We know now incidentally from our work on radioactive fall-out that the mixing process takes only five to ten years at the most before the atmosphere is thoroughly mixed. So even though the radiocarbon is produced at greater altitudes than ten miles, it will in a matter of a few years have come down to the lowest levels where it can be incorporated into the plants.

The plants eat the radiocarbon from the cosmic ray manufacture and then we eat the plants and so all living things become radioactive with carbon-14. But most important for radiocarbon dating is that our contact with cosmic rays exists only so long as we continue to eat. As long as you are alive and continue to eat, you continue to absorb and ingest radiocarbon. The carbon-14 atoms in your body, which are 8300 years old on the average, have been many times in the air as carbon dioxide, have been brought down to the earth as part of the plants, or more likely have been dissolved in the great depths of the ocean. In this great span of time, the winds blow the radiocarbon around, the ocean currents mix it, so that even though the cosmic rays vary very strongly with the geographical latitude - being much more intense in northern and southern latitudes than in the equatorial - after this great period of time we should expect that the distribution over the earth would be uniform. We do indeed find that, in Nature, living matter such as pieces of wood and flesh, or other living material from various species, various locations - we find that they all have the same amount of radiocarbon in them, per unit amount per gram of carbon. That is, the composition - the concentration - of radiocarbon in the carbon of the living matter is uniform over the entire world and in all species, because of this continuous mixing. As long as we live, we are part of a giant system which is continuously

stirred. We belong to the oceans and to the air and we are all part of the same system, but our connection is through our mouths, through food.

UNIFORM C^{14} CONCENTRATION

Radiocarbon dating operates on this basic principle. Once you die, you stop eating. Once you die, the ingestion of radiocarbon is terminated. Of course, it is a characteristic of all radioactive materials that they themselves disintegrate and disappear and transform. In our case of radiocarbon, the transformation occurs at the rate of 50 per cent every 5700 years, and the result is the re-formation of the original nitrogen from which the carbon was produced. In the course of this transformation, a radiation is emitted which allows us to detect the death act of the radioactive atom. If we put, say, carbon dioxide gas obtained by burning a piece of wood in a counter, by listening to the count-rate we can detect the disappearance of the carbon atoms as they convert themselves back into nitrogen. It takes somewhat over 4000 million radiocarbon atoms to give one disintegration per minute, because the average life of radiocarbon is 8300 years, or 4400 million minutes. So you must have 4400 million radiocarbon atoms to get a detectable radiation in your carbon dioxide in your counter. Although this seems a large number of radiocarbon atoms, it is not large percentage-wise. The total number of atoms in, say, a gram of carbon is 10^{12} times this - that is, we have only one radiocarbon atom in a million million ordinary carbon atoms. This is the standard concentration in living matter. And at the time of death, all living things begin with this rate. They will have a count rate which corresponds to the occurrence of about 66 000 million radio atoms per gram of carbon - that is a total disintegration rate of about 15 per minute per gram.

The first thing in our development of radiocarbon dating was to prove that it was indeed so, that radiocarbon occurred in all living tissues and at the expected uniform level. This was done fairly quickly and it was gratifying to find that our rather simple-minded theorizing was correct. Now, as the years have gone by and more accurate measurements have been made, we find that it wasn't actually absolutely correct. There are very tiny differences between species - for example, sea life has just a little bit less radiation than it should have, for there seems to be a kind of natural barrier against carbon dioxide in the air dissolving in sea water. It doesn't dissolve rapidly.

In a general way, we went forward in our innocence finding that everything worked. I have never been connected with such a lucky piece of research. For example, we supposed that the oceans mixed rapidly, and that most of the hold-up of radiocarbon would take place in the ocean which has far more carbon dissolved as sea salts than is contained in all living matter. We had to calculate from our knowledge of the cosmic ray production rate what the expected concentration would be. If we only considered the biosphere, its expected concentration would be thirty times greater than the level which we actually found. However, we rightly guessed that the oceans would mix rapidly and that the concentration in the biosphere would be thirty times lower than the rate of cosmic ray production would seem to suggest. There is, in fact, thirty times more carbon in the ocean than in the

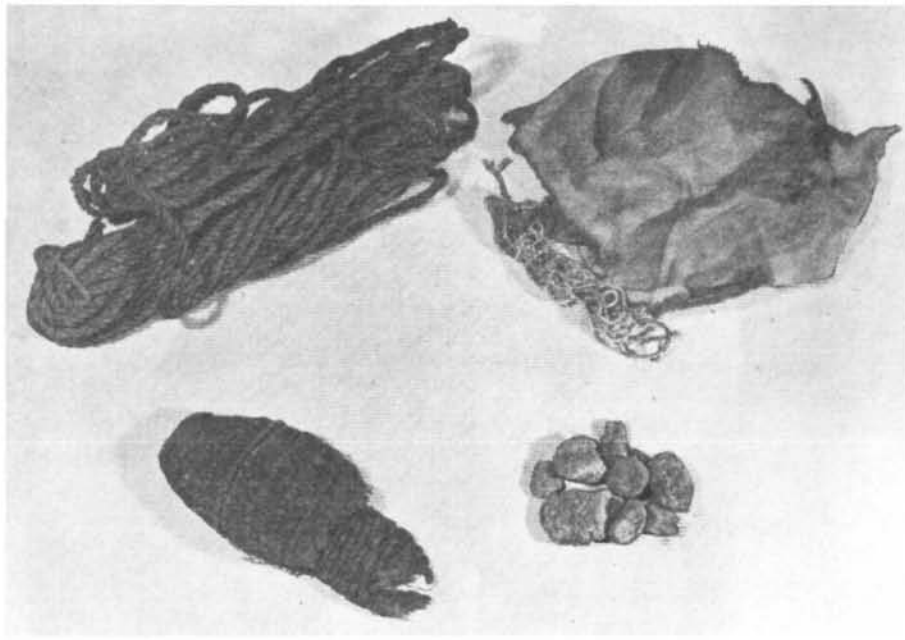
whole of the biosphere. We were lucky there. We were lucky also in supposing that the turnover of humus is rapid, or rather that the hold-up is not serious in the terms of the whole inventory. This although we knew full well that coal and oil and all organic matter of this sort would be long since purged of radiocarbon by radioactive decay, and once formed was out of equilibrium.

THE MUMMIES' VERDICT

The next stage of the research was to see if it was really so that 5700 year-old mummies showed only half as much radiocarbon as a person living today. There are no 5700 year-old mummies, the oldest ones are 4800 years old - that is, ones whose ages are relatively well-known, so that we could use them for a check. These are the first dynasties of Egypt, where the oldest recorded history applies. When you go back to the dawn of history, the certainty with which the historians know the dates has decreased. I would say that from my experience of talking with historians, they would stake their lives on 3750 years, but with anything older than that, they begin to shake a little bit. But they can go back to Sesostris III in the 12th dynasty of Egypt and argue very firmly.

So we had two periods in which to check our method - one was 3700 years and the other was about a thousand years preceding that. We were very fortunate in that our checks - with one or two exceptions - were excellent. One of the exceptions will interest you - we worked in collaboration with the distinguished Oriental Institute of the University of Chicago with the great collection that J.H. Breasted had made from Egypt. And our third object from Egypt turned out to be modern. It was one of his prize collections, supposed to be from the fifth dynasty, as I remember. This was a dark day. But having succeeded on the first two measurements, the people in the Institute checked their records and they thought it was entirely possible that he had been hoaxed and we went on and the only interpretation we have for that measurement today was that he was "sold a bill of goods". But by and large, we have had few shocks. For example, on Stonehenge we obtained 3700 years, which agreed excellently with the predictions of Professor Stuart Piggott, the great scholar of Stonehenge. Throughout Roman and Egyptian history, we have no disagreements. We haven't had very many measurements to make because in general the archeologists know the dates better than we can measure them, and it is usually as a favour to us that they give us samples. We take about an ounce of material to make a measurement - about 20 to 30 grams of fairly rich carbonaceous material is the normal amount, and in some of these objects that is too large an amount to be spared. On the other hand, we can sometimes make do with samples which would otherwise not be useful. For instance, we dated the Dead Sea scrolls - the manuscript of the book of Isaiah - by using the linen wrapping in which it was found.

I must admit that we have been a little shy of religious objects and have not sought them as subjects for research - though we would be very pleased to collaborate in establishing instruments for investigations, we have enough problems without being involved in religious questions. There



Some of the objects which have been dated by the radiocarbon method. Upper left: a 2600-year-old rope from Peru. Upper right: the linen wrapping of the Dead Sea Scroll-Book of Isaiah. Lower left: a 9000-year-old sandal from Oregon. Lower right: dung of the giant ground sloth (now extinct), 10 000 years old. (Photo: Institute for the Study of Metals).

has, however, been no serious shortage of materials back to about 3700 years with which we could check the accuracy and reliability of the method. And the answer is that the method seems to be reliable to within the error of the measurement, as it existed when we began the method in the early fifties and the error was about ± 100 years or something of that sort. More recently, extremely careful measurements with very accurate instruments have shown that there are systematic deviations, indicating that the rate at which radiocarbon was being produced was not strictly constant. A rate had been an implicit assumption at the outset, when we compared the radiocarbon in an Egyptian mummy with that in a modern man, we assumed that he lived under similar conditions. This assumed that the radiocarbon production rate at that time was the same, that the cosmic rays were the same, and that the amount of ocean water was the same - that is, that the amount of carbon dilution was the same. We have fairly good evidence that the ocean hasn't changed much, either in composition or level, in 5000 years. This is a very brief time in geological history.

COSMIC RAY VARIATIONS

But the cosmic rays is an open question. People have very little understanding of the origin of cosmic rays. We believe that they come from outside the solar system, and have very good evidence for that. But there are various

subtleties about even that because, even if they come from outside the solar system, they have to reach the earth. Cosmic rays are deflected by matter and particularly by magnetic fields, and the sun is continuously sending off ionized matter in clumps which carry locked-in magnetic fields capable of deflecting cosmic rays. My distinguished colleague, Dr. Hans Suess, of the University of California, San Diego, has sent me a manuscript entitled, "The climatic changes in cosmic ray production rate of radiocarbon". In brief, he says that when you have hot weather for a period of a century, this means that the sun is specially active in sending out lots of plasma, therefore the production of radiocarbon is especially low. In consequence, during that century your radiocarbon dates are too old, and conversely, when you have a century or two of cold weather, the sun is inactive and the cosmic rays come in better, so your radiocarbon dates are too young. The errors are like ±50 years, so it is almost within our experimental error. He has been very energetic in making lots of measurements, using tree rings for his materials, so he knows the date quite accurately, and I think there is little doubt. We have been doing work on English manor houses in the last couple of years: the historical dates are excellently known for many of these homes and we find that our agreement has improved if we make Suess's little corrections. He has made the point that there is a deviation which is small but measurable. But by and large the agreement has been gratifyingly good.

The consequences of the agreement are interesting – namely that the cosmic rays, the level of solar plasma and the earth's magnetic field have remained essentially constant and that the ocean depth has not changed appreciably – not a very surprising result.

But when we finish with recorded history, we have not used even half the radiocarbon. The way radioactive decay goes, you lose half in one half-life and then you lose half in another half-life so that at the end of two half-lives, that is 11400 years, you still have 25 per cent left. It will take ten half-lives – 57000 years – to get down to a tenth of one per cent. Even with our most sensitive methods of measurement at this time, we cannot measure a tenth of one per cent of the natural life. So radiocarbon will not apply to things older than about 50000 years – in fact when you get back to 40000 things get a little uncertain. But between the dawn of history – that is 4800 years – and 40000 years is a great span of time. We are not entirely without things for checking. The method is our main purpose in the research, and our objective has been to obtain things to check against and it was with some disappointment that we learned that history was so short-lived.

EVIDENCE OF THE GLACIERS

Within the span of radiocarbon there were three Ice Ages. It appears that an Ice Age is world-wide – at least it would be surprising if it were not. It certainly is hemisphere wide. So if we find a glacial advance occurring in North America at a certain time, we ought to find it occurring in Europe at the same time. So this was one of our critical prehistorical checks. We took material from a forest in Wisconsin which had been pushed over by

a southward-moving glacier. We measured tree trunks, we measured the soil in which the tree grew, and we measured all parts of the verdure of that forest which had been preserved when the glacier pushed some twenty feet of dirt which covered it. We got the same answer for all of these various parts – 11 400 years – to within two or three hundred years. This had several important messages for us. One was that even the tiniest fibres on the rootlets, if properly cleaned, could be used for reliable dating, because they were of the same dates as the pieces of wood on the big trees. And the humus in the soil was still authentic and reliable.

Then we went to Europe, and in England and North Germany and North France, found the same dates. Now we have found it also – limited evidence, but it looks conclusive – in the southern hemisphere.

Another epoque in human history was the advent of man in North and South and Central America. For reasons which are not entirely clear, man came to the Americas after the melting of the last ice sheet. He came 10 400 years ago, and he came at the same time to all three continents. That is in the sharpest contrast to the European situation. The oldest Englishman is 10 400 years old because he was chased out by the glacier and then the glacier swept all evidence of previous man away. That is why Piltdown worried the life out of us because Piltdown man was presumably much older than 10 400 years, and it was therefore with great comfort that we learned it was a hoax. We contributed a little bit towards discovering the hoax. However, the oldest Englishman is 10 400 years old because that's when the ice sheet left England and he walked into England – the Channel was dry. The oldest American is 10 400 years.

We can understand why the oldest Englishman is 10 400 years old for the reasons that I have indicated, but it isn't at all easy to understand why there isn't someone older in the Americas since not all the Americas were glaciated. What men did in Europe was to move to the Mediterranean basin – we have abundant evidence of man around there that goes back way beyond radiocarbon. We have just begun a new dig in Israel near the Sea of Galilee, which we think is two million years old. That is also way beyond radiocarbon, but we are interested in it as we may be able to help in dating the later phases. After we had dated about a dozen different earliest man's sites, in North America, Central America and South America and got 10 400 for each one of them, we began to believe that unlikely as it seems, it is true. As far as I know – with one possible exception – all the earliest man sites in all the three Americas are 10 000 years old, within the error of measurement. This gives us a consistency check as well as a new result in human history.

We could rationalize it and say that for reasons unknown to us, man didn't come to the Americas until the Behring straits were laid bare by the drop in sea level resulting from the glacial formation in the last Ice Age. The amount of ice was such that the sea level throughout the world fell by 150 feet. If you drop the ocean level by 150 feet, a wide stretch is dry between Siberia and Alaska and down the west coast of Alaska and as far as the State of Washington. It goes pretty far out into the ocean.

We have never been able to find 10400 year old men in Alaska itself. This also fits, you see, for the reason that that was covered in ice. He didn't come through Alaska. He walked across the Behring straits and then he came down the coast which is now submerged, and his trail is 150 feet under water. Then he came inland to about the State of Washington and he moved south, and we found him at the southern tip of South America. Our most recent date was in the highest level of the Peruvian Andes at the 10400 date.

A PREHISTORIC SHOE-STORE

Other consistency checks include the measurements of various cultures that the archeologists may not be precisely able to date, but they can pick out certain cultural characteristics of a given period. I might mention one or two. Our 10400 man was a very sophisticated person in some ways. He was a six-footer. He wore clothes the size of those that we would wear and as I have said, he covered the three continents of the Americas within the measurement of error of radiocarbon - that is within a couple of centuries. We were fortunate in finding a most remarkable cache in Eastern Oregon. A road was being dug in Eastern Oregon in the late forties. Now Eastern Oregon has many volcanoes and an archeologist at the University of Oregon, Dr. Cressman happened to warn the foreman of this particular road crew to be on the look-out - he knew that the foreman was going to make a deep cut in a pumice deposit of Mount Newbury. And the foreman did, and he called Dr. Cressman to tell him that he had found something. And in this cave which was apparently accidentally covered with pumice - like the pumice that preserved Pompeii - was found a collection of marvellously artistically woven sandals, which we date at something over 9000 years. It's legend in this country that sandals like this are common. We have actually succeeded in collecting a few samples from other sites and they date - we had one last year which we dated at 8500 years. Now these are the shoes that our prehistoric man wore. In this cave which Dr. Cressman and his crewmen found, were three hundred pairs of these shoes, neatly stacked. A shoe store ! I'll tell you how lucky we were in this research. This was before radiocarbon was invented, and he took his glue pot to lacquer these shoes but he ran out of glue. The glue ruins them for radiocarbon dating, but there were six pairs which he didn't shellac and we got those for dating.

HOW NEARLY CORRECT ?

And so it is we find in every place. We found a body of his in the Santa Rosa Island a couple of years ago. Why he didn't write is an amazing question - a man of that ability. You know the Lascaux caves in Central France have been dated at 15000 years, so beautiful paintings were painted five thousand years before our 10400 man came. It is hard to imagine that he wasn't intelligent enough. It is - to me - quite clear that these people were as intelligent as we were. Maybe they did write - maybe we just haven't found it. But in any case, they have left these remarkable works. I think you know that in the pre-historic Paleolithic era, there are many fine ancient monuments of unknown age and history - even in Egypt. We did pre-dynastic

work in Egypt and went back as far as 6500 years in a fairly continuous record, working with Dr. Caton Thompson of Cambridge. She furnished us with some remarkable samples of ancient Egyptian grain which she had found in granaries in the hills surrounding the Nile valley. The farmers nearly 1500 years before the first dynasty had filled these things with grain and they still had grain in them when she came 50 years or so ago. They were holes dug in the top of the hills, lined with straw, grain put in and then some kind of covering. We dated that grain.

In England, there is a continuous unbroken record going back to 10400 man and some of the sites are truly remarkable, e.g. the Star Carr site, excavated by Professor Graham Clarke at Cambridge. Remarkable work, at nearly 8000 years. Even in the historic periods, there are lots of areas, such as the Americas - you see we had no written records at all in the Americas, apart from the Mayas. This leaves only the circumstantial records and about all we have in many parts of America is radiocarbon. It fits reasonably into the sociological evidence of pottery and things like this, and we are building up a story in the Americas. But my point is that even in the historic period of the last 4000 years, radiocarbon does have applications in various parts of the world and in the prehistoric periods; it is essentially all we have in absolute dating.

This question of absoluteness is a difficult one. It isn't possible to say unequivocally that radiocarbon dates are correct. It is possible I think

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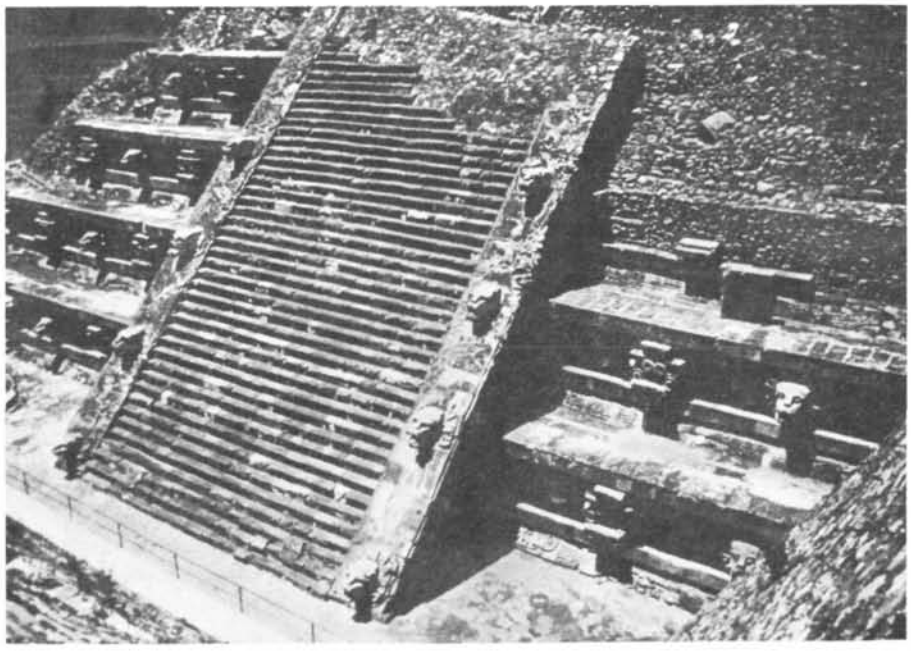
Pyramid at Teotihuacan, Mexico (Photo: Instituto Nacional de Antropologia e Historia, Mexico)



to say that in the last 3700 years, a radiocarbon date is probably accurate to within 1 or 2 per cent. In the prehistoric periods, we simply have to hope that we can develop some auxiliary check to show whether the variation of the solar magnetic field is substantial. We already have considerable evidence, in that the first dynasty of Egypt agrees pretty well. There is a tendency for the first dynasty dates to be different from the historical dates, and it would be such that Dr. Suess' conjecture might fit. His conjecture - and he himself insists that it is conjecture, because he is extrapolating - is, in effect, "If you had a really cold period, then it would be an Ice Age, and then the radiocarbon dates would be different and so we must correct the radiocarbon dates by maybe as much as 2000 years at 11000." This is about the biggest catastrophe that we can imagine at the moment happening to radiocarbon dates. In the 4000 most recent years, they are probably good to a couple of centuries. When they are calibrated in the last 2000 years, they are probably as accurate as we could measure.

There are more questions in the measurement than just the counting error - there are problems like the tree rings. You take a piece of wood - it has various rings and each year has its own radiocarbon in it. You have to be very careful to know how many rings there are and whether this wood came from the inside or the outside. We find in the old English houses, for example, that there is considerable evidence of re-use of major timbers. In the pyramid at Teotihuacan near Mexico City, we have positive proof that timbers were used in the central structures which were several hundred years old when the pyramid was built. Things like this have to be taken into account. We are now re-investigating the 12 first dynasties of Egypt with the help of the British Museum just because of this. All the graves of early Egypt were robbed and therefore there is the gravest question of authenticity in any moveable material. We have recently developed a technique of removing protein from bone and dating it. We are going to do this on the mummies as we think it is very unlikely that any grave robber would have stolen them and replaced them.