SIGNIFICANCE OF UNDERGROUND STORAGE IN TRADITIONAL SYSTEMS OF GRAIN PRODUCTION

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Until the early nineteenth century, Underground Grain Storage (UGS) has been one of the main methods of long-term preservation for large bulks of grain, if not the main one, in most cereal-growing societies. Its use was common throughout an immense area stretching from Spain and Morocco in the West, up to India and China in the East, including Southeast Europe (from Hungary to the Caucasus), South Arabia, etc. In addition, UGS was also known in East and South Africa (including Madagascar), and, before European settlement, in North America from Mexico to the Upper Missouri valley. A map of all the areas where UGS was currently used by 1800 would probably include more than a half of the grain-growing regions of the world. Conversely, only four large areas appear to have ignored UGS completely by that date, or with inconsiderable exceptions: Northwest Europe, Southeast Asia (including Austronesia and Japan), West and Central Africa, and South America. Yet in some of those areas, Britain and France for example, UGS had been important in former times, from at least the Late Neolithic to the Upper Middle Ages. To sum up all this, UGS has been, and still is in some areas, of so basic significance that it is difficult to understand how and why it was so largely neglected by both historians and technicians alike.

But is it possible to assess more precisely what was exactly this significance? And it is possible to use the relevant evidence for a better understanding of what this significance may become in the future? This paper aims at answering these two questions. Evidence for it has been gathered in the course of a research programme that we were able to launch late in 1975, owing to financial support by the CORDES (Comité des Recherches Apliquées sur le Développement Economique et Social). Since then, three conferences have been or are being organized in France on the history and technology of grain storage: Sénanque, March 1977; Arudy, June 1978; and Levroux, November 1980. Four publications have been or are being issued: Sigaut 1978; Gast and Sigaut (eds) 1979; Sigaut 1979; and Gast and Sigaut (eds) in press. This paper must be considered as a summary of all these publications.

1. HISTORICAL EVIDENCE AND SOURCES.

Evidence on grain storage in pre-industrial societies is to be found in four major kinds of sources: (1) archaeological reports; (2) travellers' accounts and other similar writings; (3) monographs written by ethnographers, geographers, etc.; and (4) the technical literature, old and new. With the exception of a few short mentions by the Latin or Arab writers, very little information is to be found in the literature before the XVIth century.

1.1. Archaeology.

Until the Middle Ages, archaeology is practically our only source of information. Of course, the main problem facing archaeologists is the precise identification of the structures that have been used for grain storage. In the case of elevated granaries, this identification has to be made with the only help of post-holes patterns, and therefore has to remain largely conjectural. Evidence concerning underground structures, such as grain silos, is of course better preserved. However, silos are always or nearly always found empty, or filled only with earth or rubbish. Rubbish can be helpful to date them, but tells precious little on what had been their real use and purpose. Finds of underground silos still containing carbonized grain are quite rare. Fortunately, archaeologists are now developing new methods, such as experimental archaeology or micro-stratigraphy of the infill, that enable us to derive much more information from the preserved evidence than was formerly thought possible.

Underground grain silos are now known to have existed from pre-neolithic contexts in the Middle East (Natufian, 9000 to 7000 BC) and in neolithic Europe (from 4500 BC on). However, these older silos are essentially small and shallow pits with no specifically recognizable form, which makes difficult to differentiate them from pits dug for other purposes. Only with the advent of iron, it seems, does the "classic" underground silo appear: more than 2 m deep, bottle-formed with a narrow neck as entrance (man hole), and of at least 1 to 3 tonnes in capacity. There can be no doubt that these "bottle-" or "gourd-"silos were designed to be airtight. It is sometimes argued that they were in fact developed as an alternative for the big storage jars used in the Mediterranean. "Bottle" silos have been found by the hundreds on Iron Age settlements sites in Britain and Northeast France. In central and southern France, many more were used in medieval times; their use was discontinued between the XIth and the XVIth centuries, except in the Southwest (Haute-Garonne, Gers, Tarn-et-Garonne), where it survived till the XVIIIth century. In some parts of Italy (Tuscany, Apulia, Sicily...) and of Spain, UGS lived on well into the XIXth century.

1.2. Travellers' accounts and ethnographical evidence.

Written evidence begins to appear during the XVIth century. But detailed descriptions of UGS become available in significant numbers only from the XVIIIth century on. By the 1800s, a rough idea of its areal distribution and of the role of airtightness in grain preservation had been acquired by the most knowledgeable agricultural writers of western Europe (in France and Italy at least, and probably also in Germany, Sweden, Switzerland, etc.; the British and Dutch do not seem to have been much interested).

The identification of airtightness as a determining factor of grain preservation is an important advance of the time. It was first explicitely made in 1708 by a writer named Reneaume, in one of the Mémoires issued by the French Académie Royale des Sciences in Paris. This realization was important, although it has already been done long before by the Roman writer Varro, living in the first century BC. The only thing that Reneaume added to Varro's was the result of his own observations on the loss of germinating power with time in stored seeds. Subsequent ethnographical literature only confirms how general was the awareness of airtightness as a factor of successful grain preservation in pre-industrial societies. Details given on the ways silos were dug out, lined, filled and stopped up, as well as on the danger of suffocation when entering them too soon when opened to be emptied (a burning lamp could be used as a means to detect "foul air"), show without a doubt that airtightness was consciously aknowledged and looked for by UGS users everywhere.

1.3. Experiments on UGS and AGS since 1819.

So, around 1800, the growing body of agricultural writers in Northwest Europe had acquired a roughly correct idea of UGS functioning essentially as AGS (Airtight Grain Storage). But this idea was still far from being precise enough to be operative. Local circumstances and skills making for successful long term preservation of grain underground were unsufficiently understood to be replicated elsewhere. The very few experiments attempted before 1800 were complete failures, as far as it is possible to tell. For the first experiments to be properly recorded began only in 1819. They were made by an industrialist named Ternaux at Saint-Ouen, a suburb lying a few miles north of Paris. Ternaux's experiments gave mixed results.

In fact, they were made under so unfavourable circumstances — the silos were dug into a wet alluvium, and grain was stored in them without caring for its humidity — that the mere fact that the grain was not completely rotten after several years is by itself a remarkable result! But although not quite rotten, except for some spots in direct contact with the walls, mouth or bottom of the silos, the grain had plainly deteriorated. The bread made from it was eatable, but somewhat bitter and acrid in taste. For practical use, therefore, the Ternaux's experiments were a failure. But it is from them on that a really scientific literature on grain storage can be said to have been born. Their impact was considerable. It is at that time that the word "silo", from Spanish origin, was introduced in the international literature. Ternaux's experiments were not the only ones, besides. At least nine different series of experiments are known from the period 1819-1830, in France only. In some of them, airtightness was achieved by the use of containers or ordinary storage rooms lined with sheets of lead welded together.

Although by and large successful, this way of achieving airtightness proved self-evidently too clumsy and expensive for current use (in addition, lead sheets teared up easily, and the danger of lead poisoning was already known).

Nevertheless, the idea of AGS was not given up. It proved (it still proves) so attractive that new experiments were attempted again and again ever after, up to the present. A chronological list of these experiments, as far as they are known to us (Table 1) strongly conveys the impression of a wavelike pattern. Every 30 years or so, it seems, i.e. at each new generation, a fresh wave of interest for AGS rises and subsides, leaving behind some more results, more or less favourable, but remarkably few actual implementations. The only AGS capacities ever built, to my knowledge, are gathered in Table 2. Except in Argentina, they were usually small, and even negligible statistically. In Argentina, AGS capacities in 1977 did not amount to more than about 14% of the total grain storage capacity of the country.

How are we to explain this wavelike pattern of interest and disinterest for AGS in the last 160 years — with perhaps another wave now, just about 20 years after the preceding one? There is no doubt a time factor. Each generation tend to ignore or to underrrate what has been done by the preceding one. After 20 to 30 years, experimental results, if not quite forgotten, are always looked on with some suspicion, rightly or wrongly. But this generation factor is certainly not sufficient for an explanation. For, if AGS did not answer its supporters' expectations, why was it tested again and again? And if it did, how is it that it could never be industrially developed? The answer, or answers, obviously require a systematic comparison between AGS and other available methods of grain preservation in various contexts. One would expect such comparisons to have been a matter of course in all the experiments listed in Table 1. But in fact, they never were. With rare exceptions, like Kondo and Okamura in the 1930s, or Pixton, Hyde *et al.* at Slough in the 1960s, a precise comparison between AGS and alternative methods under controlled circumstances ("everything else being equal") was never really achieved. Granted, to maintain "equal" circumstances in long-term grain preservation experiments is a tricky business. (One has first to decide which parameters can and must be maintained "equal", of course.) But the fact remains that it was infrequently attempted, and still more rarely achieved. As a rule, results of AGS experiments were assessed, not against results of parallel experiments under conditions as similar as possible, but either against samples of the stored grain kept in the office or laboratory, or against some standard criteria of grain quality.

That is not to say that all AGS experiments have been valueless. Quite the contrary. Usually indeed, AGS has been tested under exceptionnally unfavourable conditions, either out of sheer enthusiasm for the idea (as in the case of Ternaux), or because those conditions were a new problem, to be solved only by new methods anyway — as in the case of AGS of damp grain for fodder in the last 15 years. Two conclusions can be drawn from all this; 1, that AGS was never seriously considered as a potential

TABLE 1. MAIN EXPERIMENTS ON UNDERGROUND GRAIN STORAGE, 1819-1960 (Dry grain).

Period	Authors	Countries	Comments
1819-1830	Ternaux, and a number of others	France, mainly Paris & suburbs	At least 9 series of experim. recorded, most of them large scale and over several years
1852-1862	Doyère	France, Algeria, several places	Large scale exp. Emphasis on underground silos lined with sheet-iron. First assessments of upper limit of grain humidity for safe preservation
1878-1880	Müntz	France, Paris	Large, elevated bins of sheet-iron; fodder-grains (oats, maize, horse beans, etc.). First accurate measurements of grain respiration at various humidity levels.
1918-1920	Dendy and Elkington	Great Britain	Exp. on insect in airtight containers, not on AGS proper. First idea of AGS from India, authors quite unaware of former French experiments.
1926-1935	Kondo and Okamura	Japan	First AGS exp. with systematic checking of temperature, humidity, gaseous composition, etc.
1936-1939	Blanc	France, Le Chesnoy	Half scale exp., metal and concrete bins.
1942-1947	Lopez	Argentina	Emergency UGS, large scale
1952-1960	Oxley, Hyde and others	Great Britain, Slough	A number of various laboratory and large scale field experim.
1956-1965	CNEEMA	France, Antony	Various, mostly half scale exp.

Source: Sigaut & Gast 1979: 26; Sigaut 1979: 38-43, 51, 57-58.

alternative for traditional storage methods under customary circumstances; and 2, that "everything else being equal" (insofar as it makes any sens to say so), AGS has a wider range of possible use than non-AGS methods.

To make complete this historical survey of AGS experiments, it must be added that the new possibilities offered by airtight receptacles were soon explored. Experiments, or at least explicit proposals, of grain storage under vacuum or in desoxygenated atmospheres (burnt air, nitrogen) were made in France as early as the 1860s. But of course, like AGS proper, none of those methods proved suitable for large scale applications.

2. IDENTIFICATION AND COMPARISON OF GRAIN STORAGE TECHNIQUES.

2.1. Identification as a method.

At this point, what is needed is a way to identify each technique of grain storage with precision, and without any ambiguity. This is the only means to compare these techniques to each other, and perhaps to better understand what were, or are, the real alternatives facing people of different societies in their choice of one or several among them.

A system of identification for some agricultural and food preservation techniques, including grain storage, has been proposed (*in* Sigaut and Gast in press). The basic idea is that any one technique can be unambiguously defined by crossing the two following criteria: (1) the specific thing or *product*, to which (2) a specific mode of *action* is applied. This normally results in a double-entry table, where the various possible products are listed vertically, and the various modes of action are listed horizontally. In such an identification table, each square contains one "family" or "kind" of techniques. Some square may be void, of course, either because we still do not know actual examples of the corresponding technique, or because this technique appears physically improbable or impossible.

This identification table for grain storage techniques is rather complex. It cannot be presented here, if only for typographical reasons. Nor is it possible to mention here all the grain storage and preservation techniques thus obtained (for this, cf. Gast and Sigaut, in press). Only some results can be given here. But it should be clear that these results would be valueless speculations if they were not based on this systematic work of identification.

2.2. AGS and the storage of loose grain in bulk.

Grain products are very numerous, and each of them is or has been an important item of storage somewhere or sometime. For our purpose here, however, only three products are to be considered: (1) spikes, ears or cobs; (2) sheaves; and (3) loose grain. The point is that in pre-industrial societies, only loose grain was stored underground. Three exceptions to this rule only are known to me so far: in Somalia, in Mauritania, and in pre-settlement America; but they do not seem to be very important. This fact means that UGS could be possible and useful under two sets of circumstances only. First, when grain had to be transported over large distances, which implies the existence of large consumption centres, i.e. towns. Or second, within peasant societies themselves, when grain was customarily threshed immediately after harvest. The latter was mainly the case in most parts of the huge area alluded to before, from Spain/Morocco up to China and India. Throughout this area, the use of animals for treading out the grain has been known for millenia. With large quantities of loose grain to be disposed of by the muddle of the summer, UGS was there an obvious solution. It was safer and cheaper than any possible alternative devised ever since, except fully mechanized systems.

Outside this area, threshing was traditionnally done by human labour only, with the help of sticks, mallets, pestles or flails. This hand-threshing was rarely done all at once after the harvest (as, for example, in western France), but rather little by little, according to the peoples' needs for food or money. The main part of the grain had therefore to be stored unthreshed, that is on the ear or cob, or in sheaves.

2.3. AGS and surrounding techniques.

So, threshing techniques are a crucial factor in the choice of storage techniques, as is well known anyway by every European farmer old enough to remember what meant the change from harvester-binder to combine in the 1950s. We may ask, for instance, if the decline of UGS in Britain and northern France after the Iron Age does not point to a replacement of animal treading by hand threshing. However it may be, the fact is that the big barns used both to store the grain in sheaves and to thresh it during the winter months are a new feature of the European landscape in the High Middle Ages. They do not seem to have ever been known outside Europe.

This consideration of threshing techniques, therefore, directly leads to building techniques. It is self-evident that the building of big barns required considerable amounts of labour, money and skills. But whereas barns are characteristic of the storage of sheaves, elevated post-granaries are often characteristic of storage of grain on the ear or cob. Maize everywhere, but also millets and spelt in pre-industrial Europe, rice in Indonesia, and most tropical small grains, are harvested ear by ear. This may be due, either to the morphology of the plant itself (maize), or because of the lack of more efficient tools (sickles), or because the straw is not wanted or cannot be transported, or to a lot of other reasons. But as a rule, harvesting ear by ear goes with delayed threshing and storage of the ears. The elevated post-granaries, so conspicuous in the African landscapes, but also to many parts of Asia and even of Europe (northwestern Spain, Balkan peninsula) are very often linked with this mode of storage. In humid and cool climates, they are built with perforated walls, in order to let the air in, to allow for a progressive drying of the ears or cobs. Cribs are only the modern variant of a much older pattern.

2.4. Climatic factors.

Climate is of course a crucial factor. After all, the stored grain is an eco-system, and the problem of grain preservation is basically an ecological one. But climate never affects any one technique single-handedly, in a simple, one-way fashion. Without a previous awareness of the complex relationships between neighbouring techniques (storage, threshing, harvesting, building, etc.), a true appraisal of the impact of climatic parameters is hardly possible.

The first of these parameters is the setting of the growing cycle against the rainy/dry periods of the year. Cereals harvested at the beginning of a rainy season are never stored underground. This was the case in mid-latitude Europe with millets, spelt, buckwheat and later maize, and in northern Europe of every kind of cereals. And conversely, millet was stored underground in ancient China, in astonishing large quantities, because fall and winter are dry seasons there. So, the main areas of UGS are not simply "dry" areas. They are areas where harvest can take place under such conditions as will ensure a sufficient dryness of the grain. Doyère has shown by studying UGS in southern Spain in the 1850s, that the humidity level of the grain stored in silos rose slowly, finally reaching levels incompatible with its further preservation. Grain had then to be taken out and dried in the sun. Of course, the lower its humidity when first buried, the longer grain could stay in one silo. In Almendralejo (Estremadura), Doyère reported humidity rates of 6 to 9% after harvest (presumably wet basis), and of 12 to 15% after two years underground. It is unfortunate that studies of comparable precision on traditional UGS systems have not been replicated since Doyère's time.

This regular rise in grain humidity was so well-known that in many parts of Italy, the "increase" of the grain kept in *fosse* or *buche* — 1 to 2% in volume per year — was the rent paid to their owners (it being sometimes the state itself). Water vapour entered the grain from the walls, bottom and mouth of the silo, so that after some time, the outer grain layers were quite damper than the inner layers: extremes of 12% and 19% have been reported by Doyère. Although quite detrimental in a way, soil humidity had also perhaps its necessity, up to a point, for achieving a sufficient degree of airtightness. For an extremely dry soil would have been too permeable to air.

2.5. Food habits and grain quality.

Another point of interest in this process of slow grain humidification in confined atmosphere, is the fermentations it caused. The exact nature of these fermentations is not known. They began with the outer layers, of course, and reached gradually toward the centre of the mass. Sometimes, a silo was drowned by exceptionally heavy rains, and all the grain was fermented. But this fermented grain was by no means lost grain. In North Africa, it was called *hamum* ("hot"), and sold at a rather higher price than ordinary grain for making *couscous* (Holtz, in Sigaut 1978: 118; Vignet-Zunz, in Sigaut and Gast 1979: 216). In some parts of India, rice is put into underground silos, not so much for preserving it than for "curing" or "ripening" it more quickly, a process said to be necessary to improve its cooking and digestive qualities (Ramiah 1937, in Sigaut 1978: 18).

Clearly, "cured" grain, whether accidentally or intentionally, can only be valued in societies where it can be consumed otherwise than made into bread. This is the case with rice anyway, but in the Far East, there is a sharp contrast between areas like the Indochinese Peninsula, where freshly harvested rice is highly preferred over old rice, and areas like several parts of the Indian subcontinent, where conversely "cured" rice is preferred, to the point that fresh rice is deemed unfit for human consumption. A precise delimitation of the two contrasted areas has not been attempted, as far as I know, nor is it possible as yet to propose any tentative explanation. In the Mediterranean, the problem looks simpler since bread-making is clearly incompatible with grain fermentation. The gradual taking over of bread at the expense of other modes of grain consumption was certainly an important factor in the decline of UGS in Europe.

No serious and recent studies of grain "cured" or "ripened" in UGS are available, so far as is known to me. But the old experiments by Ternaux in the 1820s, by Doyère in the 1850s and by Blanc in the 1930s perhaps give us a clue. These experiments were very complete, including milling and bread-making. It was observed, for instance, that the somewhat "deteriorated" grain yielded at milling less flour, less bran and more grits than usual, so that it had to be milled one or two more times than usual in order to give the same quantity of flour. The flour from Blanc's experiments was analyzed; it proved all the richer in minerals (and bran symmetrically all the poorer) than "deterioration" had gone farther (in Gast and Sigaut 1979: 33-34). Such results tentatively suggest some analogy with parboiling. Lacking proper experiments on the two processes, one has to be very careful with this analogy. But the idea that the "curing" of grain by fermentation in UGS may resemble a kind of slow and cool process of parboiling is presently the only hint that can be done.

2.6. Insects.

This is the last, but obviously not the least factor to be mentioned in connexion with UGS. Our means of controlling storage pests have so fantastically improved during the last 50 years, that it is hard to imagine how people were and felt unarmed and hapless against insects before. In West and central France in the XVIIIth century, the arrival of the Angoumois Grain Moth (*Sitotroga cerealella* Oliv.) spelled disaster. Keeping grain in sheaves had been the best means to control the grain beetles (*Sitophilus* sp.). But now grain in sheaves also was attacked by the new moth. What could be done next?

This is the question to which Réaumur, and later Duhamel du Monceau and Tillet tried to find an answer. It provided the impetus for the first experiments on grain storage by Duhamel in the 1750s. A century later, in the 1850s, a fresh burst of activity by the same pest directly led to Doyère's studies and experiments on UGS and AGS. From an analysis of the literature of the time, it can be concluded that in areas without cold winters, there was no efficient way to protect large bulks of grain from insect attack, except UGS, or AGS.

CONCLUSION

Although many details are still lacking, the picture of UGS in pre-industrial societies is by now pretty clear. It was practically the only means to keep large quantities of loose grain free from insect attack for significant lengths of time in areas with mild winters. It was also cheaper than alternative methods requiring either large buildings (sheaves stored in barns) or both large buildings and much manpower (loose grain in layers with frequent shovelling). But UGS had the specific drawback that a progressive dampening of the grain could not be prevented. This dampening could be coped with when the grain was buried in a very dry state, or it could be tolerated and even looked for when food habits made fermented grain a valuable item in the diet. But in any case, fermented grain was unfit for making bread of the quality required by European town-dwellers by the XVIIIth century, and this is probably one of the main reasons why UGS could never find a wide acceptance in northern Europe.

What can be concluded from this historical survey for the future?

The future of AGS, if any, may lie in two directions. First, as a general storage method in hot countries, where cooling the grain by aeration is impossible. The main problems to be solved in such countries are perhaps those of the skills necessary to operate AGS on a routine basis. An extensive study of the knowledge and skills of craftsmen in countries where UGS lives on would certainly be helpful. The second direction would perhaps be to look at AGS as a residueless method of desinsectisation. But is it possible, with the use of atmospheric gases only, to achieve the complete desinsectisation of cool grain in a sufficiently short time? The main drawback of desoxygenated atmospheres is that they kill insects only insofar as they are active, i.e. at comparatively high temperatures (18° to 20° C and more). Cool grain takes a long time to be made insect-free by AGS alone. But there is a kind of gaseous combinatioh that has never been tried, as far as I know: mixtures containing *more* than the usual 20% of oxygen. What would be the effects of such superoxygenated atmospheres on insects at their various development stages (and also of course, on the grain itself)? Every conceivable mixture of atmospheric gases sems to have been extensively studied, except this one. This will be my last concluding remark.

TABLE 2. AIRTIGHT STORAGE CAPACITIES, MODERN		
Country, date	Type of buildings	Total capacity
France, around 1860	Silos "Doyère" (underground bins, lined with sheet-iron)	550 t
France, around 1880	Elevated iron bins of the Cie des Omnibus (Paris); fodder grains for tramway horses.	21000 m3
Argentina, 1947-	Horizontal bins, half underground, lined with concrete, etc.	2500000 t
France, Venezuela, Morocco..., 1952-60	Vertical steel bins, built by French firms or expertise	(?) 60000 t
Cyprus, Kenya, 1960-1970	Invert. conical bins, half underground, concrete lining and roof, built by British firms or expertise	148000 t

Source: Sigaut 1979: 39, 56. Figures compiled from various kinds of sources, sometimes second-hand, not to be considered as exhaustive.

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