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COST-EFFECTIVE LONG-TERM SEED STORES

International Board for Plant Genetic Resources

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COST-EFFECTIVE LONG-TERM SEED STORES

A report of the meeting
of a Sub-committee
of the IBPGR Advisory Committee on Seed Storage

held at Reading, UK
1-3 April 1985

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PREFACE

The Board requested that a Sub-committee of the IBPGR Advisory Committee on Seed Storage should meet, consider and report on cost-effective long-term seed storage with particular emphasis on alternatives to conventional long-term seed stores operating at the IPBGR preferred conditions. This report discusses the issues raised at the meeting and lists the Sub-committee's recommendations and conclusions.

INTRODUCTION

Preferred standards for long-term seed storage

1. The 1973 Report of the FAO Panel of Experts and the 1976 IBPGR Report of the Working Group on Engineering, Design and Cost Aspects of Long-term Seed Storage Facilities introduced the concept of preferred standards of long-term seed storage for genetic resources conservation. These preferred standards specificed storage of the seeds at 5 ±1% moisture content in hermetic containers at a temperature of -18°C or less (IBPGR, 1976).

Genebanks and designated base collections

2. It is thought that there are now more than 300 institutes which store seeds for genetic resources conservation. Hanson, Williams and Freund (1984) list more than 100 such institutes. Fifty-five of these operated at the preferred conditions for long-term storage in 1984; since then several additional institutes have upgraded their seed storage facilities. Thirty-eight of these long-term stores form the global network of base collections designated by the IBPGR.

Design criteria and cost estimates for conventional genebanks

3. The IBPGR has provided design criteria and capital and running cost estimates for long-term seed stores (Cromarty, Ellis and Roberts, 1982). The 1981 capital estimates varied between US$38 000 and 238 000 for a purpose-built cold store (50-500 m^3) and drying room (25-75 m^3), plus US$600-1000 m^{-2} of floor area for a basic building to house these facilities. Table 1 provides a summary of capital costs for a 100 m^3 cold store plus ancillary facilities, but see Cromarty et al. (1982) for further explanation.

4. Equations to enable the running costs of cold stores to be estimated were also provided. For example, those of a 100 m^3 store with 200 mm insulation operating at -20°C in an ambient temperature of 25°C would be between 6000 and 7000 kWh/annum, provided the store had been built to the very high specifications provided in the report.

Consideration of alternatives for cost-effective long-term seed storage

5. However, there has been much concern that some genebanks operating cold stores have reported very high running costs; and that some projected genebanks have had very high capital costs. For these reasons the Board requested that a Sub-committee of the IBPGR Advisory Committee on Seed Storage be formed to consider and report on cost-effective long-term seed storage with specific emphasis on the following topics: non-conventional energy; back-up storage in permafrost; use of caves; and up-to-date application of physiological principles to seed drying and hermetic storage at ambient temperatures.

6. The members of the Sub-committee, listed in Appendix I, adopted the agenda shown in Appendix II. Rather than provide a detailed account of the meeting, the Sub-committee resolved that a report considering the various issues raised would be of more use, and so Dr. R.H. Ellis and Prof. E.H. Roberts, University of Reading, UK, were delegated to prepare this report.

Table 1. Estimated costs 1/ of a basic genebank and ancillary facilities capable of holding 20 000 or more, accessions 2/ derived from Cromarty et al. (1982)

Item	Floor area (m^2)	Costs (US $)
100m^3 cold store	(40)	28,000
Shelving for above		23,000
Drying room	(10)	11,500
Laboratory equipment and office furniture		50,000
Buildings		
Cold store	40	40,000
Machinery room (for above)	10	10,000
Drying room	10	10,000
Preparation rooms	30	30,000
Laboratory	40	40,000
Store	20	20,000
Offices	20	20,000
Toilets/services	10	10,000
Meeting room	15	15,000
Corridors, passageways, etc. (20% of above)	40	40,000
	235	347,500

1/ 1981 prices for the first 4 items. Increase these by 30% to 50% for an approximate estimate of 1985. The major cost is that of the building, current estimates for which must be obtained lo the UK 1985 costs are US$900-1400 m^{-2}. Hence the assumption of US$1000 m^{-2} in the table.

2/ Each accession is assumed to occupy a 0.88 litre cylindrical metal can (e.g. 17 000 wheat see smaller-seeded species and/or fewer seeds per accession many more accessions could be accommod example, this store could accommodate 400 000 4000-seed accessions of Allium spp. It is impor designing the store that the number of accessions to be stored and their size is taken into acc only will an overlarge store be unduly expensive initially, but subsequent running costs wil higher than necessary.

SUMMARY OF THE SUB-COMMITTEE'S CONCLUSIONS

Conventional genebank costs

7. The preferred standards of storage conditions recommended by the IBPGR for the long-term storage of seeds for genetic conservation can be achieved without excessive capital or running costs, providing the store is designed for the purpose.

Deep-freeze cabinets

8. For many collections - particularly those of small-seeded species - the most suitable and cost-effective method of achieving the preferred conditions of storage is to dry the seeds, seal in hermetic containers and then use 1, or several, deep-freeze cabinets for storage. These cabinets can be located within an existing building.

Alternatives to conventional genebanks

9. There is a need to distinguish between alternative sources of energy and alternative storage systems. Only in special circumstances may alternatives to the use of cold stores or deep-freeze cabinets cooled by refrigeration compressors powered by public electricity be possible. This report discusses the main alternatives and the circumstances under which they might be employed.

10. It is clear that in many circumstances the use of alternative energy sources, or alternative refrigeration systems, or alternative storage systems would not be appropriate on grounds of economy or reliability.

11. Nevertheless, where financial resources are limiting, it is now clear that medium-term storage of many species using systems involving thorough drying and hermetic storage without refrigeration are viable alternatives, providing store management is good.

12. The Sub-committee was uncertain as to whether storage of seeds in liquid nitrogen should be classified as a conventional or as an alternative storage system, but concluded that liquid nitrogen storage should remain classified as a potential alternative at present since it has not yet been recommended as generally suitable for long-term seed storage by the IBPGR Advisory Committee on Seed Storage (see para. 69-72).

Comparison of alternative and conventional storage systems

13. The Sub-committee concluded that the most useful product of its deliberations would be a summary table enabling rapid comparison of the advantages, disadvantages, costs and special requirements of different systems. This is provided in Table 2. Further information is provided in the body of this report.

Other costs

14. Genebank costs are not limited to the initial capital and subsequent running costs of a cold store, or their equivalent in alternative systems. The costs of monitoring, regenerating and distributing accessions may differ among different storage systems. Consequently any comparison of different systems must also consider differences in these costs.

Table 2. Comparison of different systems for the storage of seed accessions for genetic resources conservation

System		Period of Storage	Scale of Operation*	COST§		CONSTRAINTS			Reliability	Other Comments
				Capital(US$)+	Running	Species	Climatic	Other		
Conventional (refrigerated) cold stores	Domestic deep-freeze cabinet(s)	Long-term	5 or less cabinets containing 3000 or less accessions (2.5m³ or less)	$2400 - 3900 (5 cabinets) plus $1000 for standby generator plus $375 - 675 for one spare cabinet	up to 20 kWh per day (2 to 6 kWh per day per cabinet)	None (suitable for any orthodox species)	None (anywhere)		Good	Assumes a suitable room exists, i.e. excludes building costs. Assume a 10 to 15 year write-off period for the cabinets.
	Free-standing	Long-term or medium-term	3m³ or more; 1500 to 40000 accessions (modules 3m³ to 50m³)	$4100 (3m³) to 47500 (50m³) including standby generator	15 (3m³) to 130 (50m³) kWh per day	None (suitable for any orthodox species)	None (anywhere)		Good	Modules from 3 to 50m³. Use more than 1 module if 50m³ inadequate. Shelter (at additional cost) must be provided for the free-standing module. Assume a 20 year write-off period for the modules, but a 7 to 10 year write-off period for the refrigeration plant.
	Purpose-built	Long-term or medium-term	Above 3m³	Typically at least twice the above	0.17-5.00 kWh per m³ per day	None (suitable for any orthodox species)	None (anywhere)		Good	Excludes building costs. The doubling of the capital costs compared with free-standing modules is mainly due to professional services. Assume a 7 to 10 year write-off period for the refrigeration plant. Variation in running costs dependent upon store size, design and ambient temperature.
Liquid nitrogen (lN_2)	Self-sufficient (own lN_2 production plant)	Long-term	15000 to 45000 (2000-seed) accessions (5-15 vats)	$13000 per vat plus $20000 to 40000 for lN_2 holding tank (6000-16000 litres) plus $67000 for lN_2 plant (adequate for up to 15 vats)	400 kWh per day for 130-365 days per year (5-15 vats respectively) for own lN_2 manufacturing plant	There are a few species for which lN_2 storage is not recommended. In addition lN_2 storage is less suitable for large-seeded species.		Reliable electricity supply: lN_2 plant requires high starting currents	Development programme at NSSL, Fort Collins, USA for genebank operation almost completed	Excludes building costs. Assume a 10 year write-off period for the lN_2 plant. Write-off period for the lN_2 vats is unknown, but is assumed to be > 15 years.
	Commercial supply of lN_2	Long-term	Almost any number of accessions; vary size and number of vats accordingly.	e.g. $13000 for one vat to store 3000 (2000-seed) accessions, but see Other Comments.	10 litres lN_2 per day ($1.25-10.00 per day) for each vat holding 3000 (2000-seed) accessions	There are a few species for which lN_2 storage is not recommended. In addition lN_2 storage is less suitable for large-seeded species		Requires reliable commercial supply of lN_2	Development programme at NSSL, Fort Collins, USA for genebank operation almost completed	Excludes building costs. Capital costs assume that a lN_2 holding tank is provided for the gene bank by the lN_2 supplier. (If not add $20000 to $40000 to the capital cost for a 6000 to 16000 litres holding tank.) Write-off period for the lN_2 vats is unknown, but is assumed to be > 15 years.

Table 2. Comparison of different systems for the storage of seed accessions for genetic resources conservation (Continued)

Natural environments	Mines in permafrost e.g. Nordic Gene Bank security store	Medium-term, but long-term for seeds with good storage characteristics	Any	$15000 for 8500 accessions (12 m³) ¶	Cost of inspection and maintenance	None (suitable for any orthodox species)	permafrost	Geological stability, security and access	Dependent upon geology (e.g. probability of rock falls, explosions, flooding)	Does not include safety costs, e.g. roof supports, ventilation. Write-off period for the 'store container' unknown, but assumed to be more than 25 years.
	Antarctic	Long-term at surface temperatures; medium term in rock, but long-term for seeds with good storage characteristics		Very substantial	Cost of inspection and maintenance (which could be considerable)	None (suitable for any orthodox species)	Antarctic	Ice movement, security and access	Unproven, but theoretically good	Access difficult, problem of territorial rights.
	High altitude (>3500m in temperate regions, >5000m in tropical regions)	Medium-term, but long-term for seeds with good storage characteristics	Any	Similar to permafrost in an existing cave	Cost of inspection and maintenance (which could be considerable)	None (suitable for any orthodox species)	Mean temperature of 0°C or less	Access	Dependent upon geology (e.g. rockfalls, flooding)	Access generally difficult, but worth considering if access is not a problem Write-off period for the 'store container' unknown, but assumed to be more than 25 years.
	Ambient	Mainly medium-term, but extremely dependent upon species, seed quality, seed moisture, store location and design and thus may range from short- to long-term	Any	From $0.25 per accession upwards for containers and filing system, but extremely variable	Cost of inspection and maintenance	None if short-term storage acceptable, but only good quality accessions of good storers for long-term storage	Select site which provides lowest mean temperature inside store	Capacity to regenerate accessions at short notice	Extremely dependent upon accession monitoring and regeneration policy and practice. Requires highest standard of genebank management	Excludes building costs. Building design can be altered to minimise heat gain from solar insolation and maximise cooling of building by prevailing winds and timing of ventilation. Maintenance of seeds at low moisture contents essential for this method.
	Radiative cooling	Medium-term, but long-term for seeds with good storage characteristics	e.g. 40m³ (32000 accessions)	$31000 for a 40 m³ store	Cost of inspection and maintenance	None (suitable for any orthodox species)	>300 days per year cloudless nights and mean night temperature of 0°C or less		Untested, but currently under development in Argentina	Includes building costs (1983 Argentinian estimates). Building design and location require survey and simulation. Regular, preventative, maintenance is likely to avoid any requirement to replace the store. Hence no write-off period provided.

§ All capital and running costs are for the store alone. No attempt is made here to provide cost estimates for ancillary facilities (e.g. offices, laboratories, drying room).

* In this summary for comparative purposes an accession size of 4000 wheat seeds (occupying 0.2 litres) has been assumed, except in the case of liquid nitrogen storage where - since the monitoring frequency is likely to be reduced - a smaller accession size of 2000 wheat seeds has been assumed.

+ Capital costs include those of accession containers and an accession filing system, but exclude building costs except for the radiative cooling system.

¶ With no filing system and 500-seed accessions, NGB estimate that the store could hold 70,000 accessions at a total cost of US $182000 of which $ 169000 is the glass ampoule cost

INFLUENCE OF DESICCATION AND REFRIGERATION ON MONITORING AND REGENERATION FREQUENCY

Medium- or long-term storage?

15. The period of storage indicated in Table 2 for the various alternative systems varies from short- to long-term. This section of the report considers the relative merits of desiccation and refrigeration and indicates that the choice of storage system can affect the workload required to maintain accessions.

16. Hermetic seed storage at 5 ±1% moisture content (wet basis) at a temperature of -18°C, or less, has been specified as the preferred standards for long-term seed storage for genetic resources conservation because this storage environment is technically achievable at reasonable cost whilst providing good storage conditions in which the loss in viability for all orthodox seeds occurs extremely slowly. In comparison with poorer store conditions, storage in such good conditions greatly reduces the frequency at which accessions are monitored (which wastes precious seeds and is labour intensive) and the need for regeneration (which is costly, difficult and beset with dangers). Moreover, stores at the preferred standards require less detailed management than those providing poorer storage environments.

17. If attempts are made to decrease costs of storage by relaxing these standards, e.g. by allowing warmer storage temperatures, then this reduction must be balanced against the increase in costs which will arise because of the requirement to monitor and regenerate accessions more frequently.

The relative merits of desiccation and refrigeration

18. Some 25 years ago Harrington formulated certain 'rules of thumb' to describe the relative influence of storage temperature and seed moisture content on seed longevity. These were: each 1% reduction in seed moisture doubles the life of the seed; and each 10°F (5.56°C, but Harrington subsequently used the value 5°C) reduction in seed temperature doubles the life of the seeds (Harrington, 1973).

19. As a teaching aid Harrington's 'rules of thumb' are a very useful approximation; they emphasize that there is an essentially exponential relationship between seed storage life and storage environment. His rules do not, however, quantify the relationship between storage environment and seed storage life because they deal with relative rather than absolute effects. Neither do they accurately reflect the relative influence of temperature and moisture on seed storage life because, while Harrington's rules are approximately correct under typical conditions of short-term commercial storage at ambient temperature, the relative effects change with the particular range of temperature or moisture content being considered.

20. As a result of research supported by the IBPGR, quantitative models defining the influence of temperature and moisture content on seed storage life are now available for several species and are under development for many more. The following points are relevant to this report.

21. Within a species, differences in longevity among accessions (which may result from genotype, and/or maternal and post-harvest environment) affect the quantal relationship between storage period and percentage viability through their effect on initial quality. These effects on initial quality affect the absolute longevity of accessions but not the relative effects of temperature and moisture content on longevity. In other words an improvement in storage conditions which doubles the

longevity of a good quality (potentially long-lived) accession will also double the longevity of a poor quality (potentially short-lived) accession.

22. The relationship among seed moisture and longevity is logarithmic and varies substantially among species (in contrast to the semi-logarithmic relationship implied by Harrington's rule). The major (but not the sole) difference in the sensitivity of different species to moisture content appears to be correlated with oil content; seeds with very high oil content are considerably less sensitive to differences in percentage moisture content than those with a low or negligible oil content; that is, the relative longevity of seeds of low oil content is increased much more than the longevity of high oil content seeds for a given reduction in percentage moisture. For example the factor by which longevity is increased in onion (high oil content) as compared with barley (low oil content) for a decrease in moisture content from 9% to 8% is 1.50 as compared with 2.00; whereas the corresponding factors for a reduction from 5% to 4% are 2.17 and 3.70.

23. The sensitivity of seed longevity to temperature is not constant but varies according to temperature range which varies on a diurnal and annual basis; that is, the temperature coefficient (change in rate of loss in viability for a 10°C rise in temperature) increases with temperature, whereas Harrington's rule implies a constant Q_{10} of 4 which, in fact, is only approximately correct over the range 16°C to 20°C. Below this range the temperature coefficient is lower and above it the temperature coefficient is higher. Different species, however, show the same (relative) response to temperature. Ambient stores and many natural storage facilities result in fluctuating store temperatures. Change in temperature per se does not result in serious problems for genebanks, but it is worthwhile minimizing the maximum temperatures which seed accessions attain within fluctuating temperature stores. Appendix III discusses how the effective temperature of seeds in a fluctuating temperature store should be assessed.

24. The accurate quantification of the relationship between environment and seed longevity allows the relative merits of desiccation and refrigeration to be assessed. For the purpose of the first comparison (Fig. 1) an arbitrary storage period of 20 years with a loss in viability from 90% to 85% over this period has been used to demonstrate equivalent combinations of temperature and moisture content for 3 species - barley, chickpea and onion. These curves must be considered in context. They are extrapolations - since the research has not been conducted over a 20-year period. Even if these extrapolations are correct, errors in determining seed moisture content, and sampling errors when assessing germination, make it very unlikely that these exact results would be achieved. Nevertheless the method of comparison is the best currently available (and a substantial improvement over that available when the IBPGR was founded). Thus in barley, if regeneration every 20 years is acceptable for accessions originally 90% viable, then storage at (for example) -20°C and 11% moisture content or storage at +20°C and just below 6% moisture content would be equally acceptable alternatives (curve a, Fig. 1).

25. Accordingly if ambient temperature were 20°C one could argue that in this case reduction in moisture from 11% to 6% prior to hermetic storage is equivalent in effect to refrigeration sufficient to maintain a store 40°C below this ambient temperature without further drying of the seeds below 11%. The costs of the former are likely to be considerably less than the cost of the latter; thus initial further drying is more cost-effective than subsequent refrigeration.

26. The isochrones (lines joining environments of equal longevity) in Fig. 1, however, being calculated for a loss of viability from 90% to 85% (a typical regeneration standard), imply a very frequent monitoring and regeneration policy (in these circumstances it would be necessary to carry out viability monitoring tests at least every 5 years). Consequently better storage environments are preferable for base

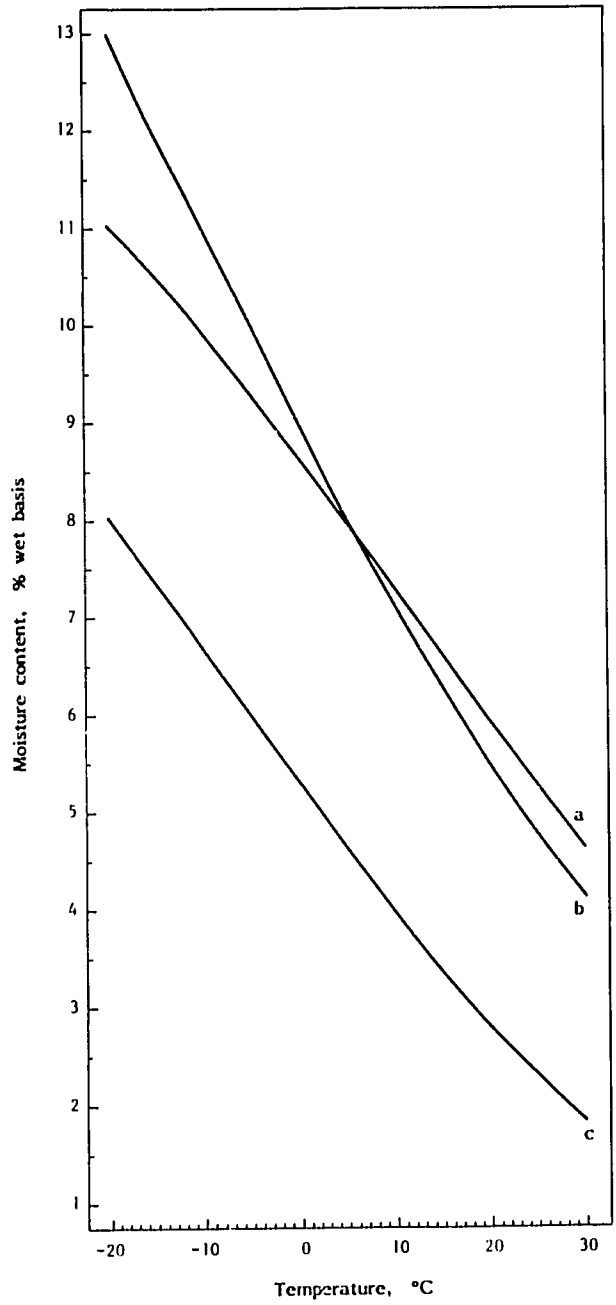

Fig. 1. Isochrones for barley (a), chickpea (b) and onion (c) showing different combinations of seed moisture content and storage temperature estimated to provide equivalent environments in terms of seed deterioration, viz: a 5% reduction in viability from an initial 90% down to 85% over a period of 20 years. Isochrones calculated from the improved viability equation and the viability constant values provided by Ellis and Roberts (1980), Ellis and Roberts (1981) and Ellis, Osei-Bonsu and Roberts (1982).

collections. The question then arises as to what environments are equivalent (in terms of seed deterioration) to the preferred standards of the IBPGR for long-term storage (-18°C with, say, 6% moisture content). Fig. 2 provides curves for 3 species - barley, chickpea and onion - which attempt to answer this question. (Note that within each species the curves join storage environments in which seed deterioration occurs at the same rate, but that longevity differs considerably among the 3 species.)

27. Work supported by the IBPGR at the University of Reading, UK and research at Wakehurst Place Genebank, Royal Botanic Gardens, Kew, UK has demonstrated considerable improvement to longevity after drying to very low moisture contents (i.e. substantially below 5%); and Fig. 2 shows that long-term storage at ambient temperature is then possible, at least for some species. However, some caution is necessary before advocating storage at ultra-low moisture contents at ambient temperatures. Firstly, it can be very difficult to dry some species (e.g. the grain legumes) to very low moisture contents (e.g. 2-3%). Secondly, potential problems of imbibition injury (due to rapid entry of water when seeds are subsequently germinated) are likely to be much more

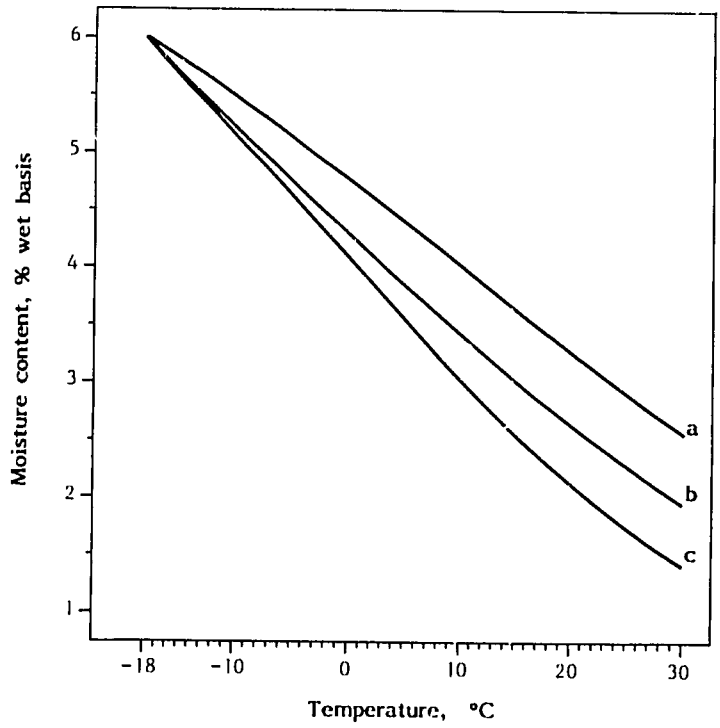

Fig. 2. The combinations of seed moisture content and storage temperature for barley (a), chickpea (b) and onion (c) estimated to provide storage environments equivalent in terms of seed deterioration to the preferred standards for genetic resources conservation of -18°C with 6% moisture content. Calculated from the equation and constants provided by the sources listed in Fig. 1. The estimates at ultra-low moisture contents (below 4%) are provisional. This topic is the subject of continuing research.

prevalent. Nevertheless, many of these problems are not insuperable (see Ellis, Hong and Roberts, 1985) and further investigations at ultra-low moisture contents (i.e., below 2%) should enable such problems to be overcome. It should be pointed out that if seeds are not stored under hermetically sealed conditions the seed moisture content will be changed depending on the relative humidity and the kind of seeds (see Figs. 3 and 4, Cromarty et al., 1982).

28. Even without further research it is suggested that, for example, cereal seeds could be maintained at 4% moisture content and +10°C rather than 6% moisture content and -18°C if it proved difficult to maintain the store at the latter temperature since these 2 sets of conditions give equivalent longevity (see curve a in Fig. 2). Of course, though, storage at 4% moisture content and -18°C would be even better since it would greatly reduce the monitoring frequency and considerably increase the regeneration interval.

Costs of monitoring and regeneration

29. The costs of monitoring are twofold. Firstly, the value of seeds destroyed in the monitoring test must be considered. Secondly, the cost of the monitoring test must be considered, because it involves considerable labour in removing a sample from the seed accession in store, setting up the germination test and then evaluating the test and recording the test result.

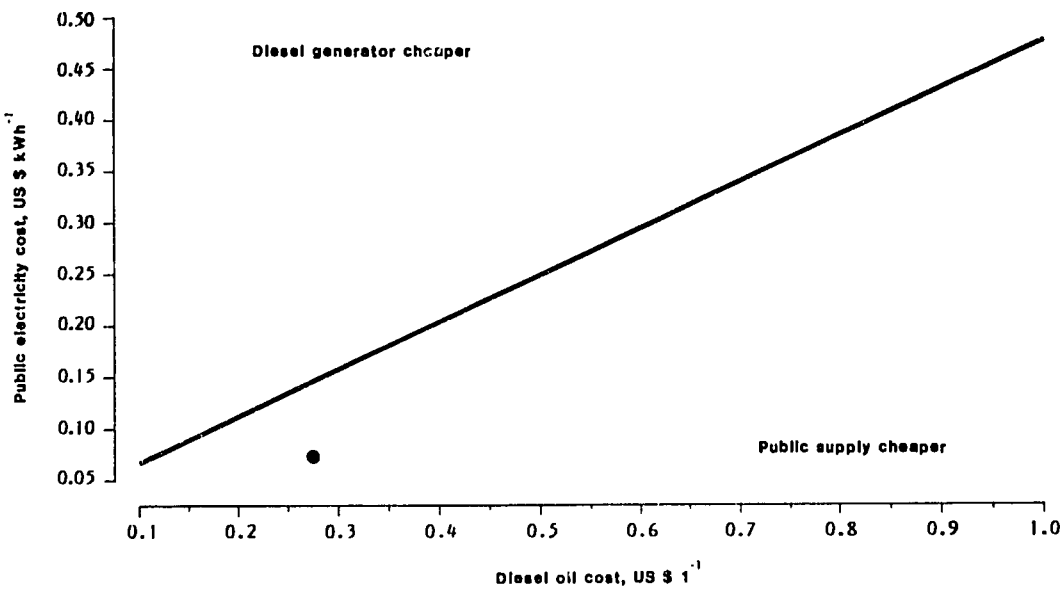

Fig. 3. Diagram to compare electricity costs from public supplies or from running a diesel generator. The solid line is where electricity costs are similar from either source: within the area below the line the public supply is cheaper than using a diesel generator; within the area above the line it is cheaper to generate electricity using a diesel generator than to purchase from the public supply. The solid circle indicates current UK prices. Clearly in this situation the public supply is the cheaper option. The solid line assumes a fuel economy of 0.453 litres per kWh generated. A different efficiency of electricity generation would require a different line to be drawn.

30. It is not possible to provide any single, reliable guide to the costs of regeneration. This is because the costs vary greatly among both species and sites. The National Seed Storage Laboratory, Fort Collins, USA, contracts regeneration to outside organizations. Thus in this case the costs of regeneration are fairly easy to identify: for example, US$300 for each cabbage accession and US$120 for each wheat accession. At the National Vegetable Research Station Genebank, Wellesbourne, UK, regeneration is done 'in house'. Consequently costs are more difficult to apportion. Initial calculations, however, suggest that the cost per accession for open-pollinated vegetable crops cannot be less than US$500.

31. Thus, in attempting to evaluate the economics of operating stores at conditions other than the preferred standards, the actual change in monitoring and regeneration costs should be determined at the particular site for the material to be maintained.

SEED STORE SITE

32. If natural facilities are being used to provide a low storage temperature without refrigeration or if an ambient store is proposed then clearly the siting of the store is a critical design factor, but siting also influences running costs and, possibly, the design of refrigerated cold stores operating at the preferred conditions.

Basic considerations

33. There are several basic, but important, factors which must be considered when selecting the site of a long- or medium-term seed store for genetic resources conservation. Although primarily concerned with refrigerated stores operating at the preferred conditions, the major factors mentioned in previous IBPGR publications are repeated below:

(i) Socially stable area within reach of security personnel;

(ii) Reliable public electricity supply and stable voltage;

(iii) Suitable substratum for foundations, adequate drainage, and absence of flooding;

(iv) Situation away from dangerous chemical or fuel storage areas; and

(v) Easy access to the area where seeds of active collections are threshed, dried and cleaned.

Note that not all of the above are adhered to in the case of some alternative storage systems (Table 2).

Effect of site on store temperature (ambient stores) or running costs (refrigerated stores)

34. In addition to the above considerations, however, it is important to recognize that the cost of running a refrigerated store, or the temperature of an ambient (unrefrigerated) store, is affected by ambient air temperature, insolation (exposure to the sun's rays) and wind.

35. Clearly where several potential sites are under consideration the ambient environment is one of the critical factors in the choice of site, since the warmer the ambient air temperature the higher store temperature (ambient store) or running costs (refrigerated stores). The following factors are also worth considering:

(i) In hilly regions, sites on northern slopes of hills in the northern hemisphere and southern slopes in the southern hemisphere may receive much less solar radiation than other sites - depending on latitude;

(ii) Natural shading from trees may be beneficial, provided the structure of the facility is not exposed to risk by root or felling damage; and

(iii) In many sites direct cooling by maximizing exposure of the structure to the wind may be possible, but this calculation requires detailed modelling.

36. In the case of refrigerated stores the effect of different ambient temperatures on running costs at different sites can be calculated using equations provided in Appendix IX of Cromarty et al. (1982). For a given standard of insulation, the less the difference between ambient and store temperature, the lower the running costs.

37. If, for reasons other than running costs (such as those given in para. 33), the site with a higher ambient temperature is chosen, then note that a higher insulation standard for the cold store will be justified - again, see Appendix IX of Cromarty et al. (1982).

38. To minimize heating as a result of solar radiation the seed storage facility should be built on a north-south axis with the cold store and refrigeration plant at the northern end in the northern hemisphere and southern end in the southern hemisphere. A thermally stable structure should be used.

39. To minimize running costs it is essential that the refrigeration plant is in the coolest location possible and well-sheltered from insolation. Water-cooled condensers and cooling towers may be considered when the wet bulb temperature is significantly below the dry bulb temperature.

USE OF NATURAL FACILITIES

Potential and problems

40. At first sight the use of natural facilities to house cold stores in order to avoid (or greatly reduce) the requirement to refrigerate, whilst still ensuring low temperatures, is attractive. Examples of such environments include natural caves, mines, high altitude sites and the Antarctic. The major problems with these potential sites for genetic resources facilities are, however, their poor accessibility, geological instability and, in the special case of Antarctica, undefined territorial rights in the future.

High altitude sites

41. Several areas of high altitude appear to be worthy of further investigation as potential sites for ambient seed stores, viz: the Himalayas, the Andes, northern China and possibly, the Atlas Mountains, but only if reliable access is available.

Natural ice

42. Storage in natural ice - for example in glaciers or Antarctica - does not seem to be of potential application for the long-term storage of seed accessions. The major problem is that of ice movement. In addition, however, ice temperatures are dependent upon ambient temperature and the depth of ice. In general ice temperatures close to the surface are similar to ambient air temperatures and will vary from only just below 0°C to -40°C (Antarctica). At great depth, ice is a good insulant. Consequently the

temperature of ice below the surface is largely dependent upon previous surface temperatures, with a substantial time lag being shown. There are also, however, substantial pressure effects which can lead to warming such that pockets of water - at close to 0°C - may be found at depth.

43. If present, nearby rock structures will not move and may (in some locations) provide a lower, more stable, storage temperature.

Rock freezers

44. The special case of utilizing natural caves to provide additional insulation for refrigerated cold stores (sometimes described as 'rock freezers') has been mentioned in Appendix X of Cromarty et al. (1982); but this is simply taking advantage of large volumes of rock as insulation rather than using the natural climate. In addition to poor access and potential problems from underground streams, such stores require an extremely comprehensive preliminary evaluation to determine each site's suitability, and specialized construction and operation during the initial 'pull down' period (roughly 12 mo) of continuous refrigeration which must result in at least 10 m of permanently frozen rock around the store, but thereafter only about one-third of the refrigeration capacity is required to maintain temperature and a standby electricity supply is needed only for lighting and heated door seals.

Genetic damage to accessions in mines or caves?

45. There has been some suggestion that the use of mines or natural caves for genetic resources conservation may introduce the risk of genetic damage as a result of increases in radiation. Although increases in radiation will increase genetic damage, the damage resulting from small increases in background radiation is inconsequential compared to the genetic damage which results from storage in environments where loss in viability is rapid. For example, it has been estimated that a reduction in viability from 100% to 50% in the absence of ionizing radiation might cause as much damage as 10 000 Roentgen of ionizing radiation. Consequently, where feasible, the use of suitable mines or natural caves is acceptable for genetic resources conservation, particularly since seeds would be hermetically stored and therefore unaffected, for example, by radon emanating from granite rocks.

Nordic Gene Bank seed security store

46. The Nordic Gene Bank (NGB) has established a seed security store in a disused section of a coal mine within permafrost at Svalbard, Norway. There are special reasons why this site is attractive. Firstly, although access is difficult (by air, Malmo-Svalbard, 2500 km) the material in store duplicates that maintained by NGB at Alnarp, Sweden (where seeds are maintained at the IBPGR preferred standards). Thus it is only intended to access samples in store at Svalbard in the event of an unforeseen accession loss from the Alnarp collection. Secondly, the cost of maintaining the mine, gallery, entrance and periodically monitoring the fabric of the store has (and will be) borne by the Store Norske Spitsbergen Kulkompani (SNSK, Norwegian Coal Company) - a state-owned company which has a mandate from the Norwegian Government to continue mining coal in the area to preserve employment in this isolated region, (i.e. it is not envisaged that the company will close the mine should continued operation become uneconomic). More details of the NGB permafrost store at Svalbard will be found in Appendix IV.

Ambient temperature stores

47. Prior to the foundation of the IBPGR in 1974, many genetic resources collections had been stored under ambient environments - such as offices or laboratories - with

varying degrees of success. Because many of these collections were poorly managed, or simply forgotten, it was concluded that such methods of ambient seed storage were not satisfactory for genetic resources conservation over the long-term (e.g. IBPGR, 1976).

48. Evidence now available (e.g. see paras. 18-28), however, suggests that well-managed ambient stores may be satisfactory for medium-term storage for many species provided the seeds are dried to the low moisture contents recommended by the IBPGR (5 ±1% moisture content) and stored hermetically to maintain these low moisture contents. Such stores require higher standards of management, however. This is simply because deterioration will be occurring at a much greater rate than if the accessions were stored at -20°C (e.g. if ambient store temperature were 10°C, then the rate of deterioration will be roughly 12 times more rapid). Appendix V provides information on 1 ambient store which has operated for more than 15 years.

49. If an ambient store is to be constructed then the design should attempt to reduce the temperature within the store as far as is possible by passive means. The following general aspects of design are worth considering:

(i) Ensure that the roof and walls are constructed from materials with good insulating properties;

(ii) Ensure that the roof and walls are thick - both to insulate and also to damp diurnal fluctuations of heat transmission into the building;

(iii) Ensure that the external surfaces of the building are bright and reflective - to minimize heat absorption by the structure. Attempt to ensure that the external surfaces are also good emitters of long-wave radiation - to maximize heat loss from the building (e.g. at night). Some compromise between these 2 aims will be necessary; and

(iv) Ensure adequate ventilation when ambient temperature is below store temperature, but prevent ventilation when ambient temperature is above store temperature.

Very thick concrete, or mud (adobe) walls painted white are examples of suitable construction materials.

ALTERNATIVES TO PUBLIC ELECTRICITY FOR POWERING REFRIGERATED SEED STORES

50. The following alternatives to the purchase of public electricity in order to drive mechanical refrigeration systems can be considered:

(i) Photovoltaics;

(ii) Heat engines driven by solar radiation or geothermal energy;

(iii) Wind generators;

(iv) Hydroelectric generators; and

(v) Diesel generators.

Economies of scale

51. All the above solutions imply generation of electricity by the genebank itself. In most circumstances involving power supplies there are distinct economies of scale. It follows, therefore, that all the above alternatives would become cheaper sources of power where power is generated for several users, e.g. a small community, or a research institute of which the genebank is but a part.

Depreciation to allow for repair and replacement of electricity generation system

52. At first sight the first 4 of the above alternatives (para. 50) would appear to provide almost free power once the initial capital costs had been paid. In several locations the capital costs of genebanks have been met, or partly met, by aid or charity, whereas national Governments have subsequently been responsible for providing genebank running costs. It follows that direct or indirect solar energy power sources are at least superficially attractive to national Governments; but an annual allowance for depreciation should be made to enable the equipment, which has a finite life, to be replaced. A further annual allowance is necessary for repairs, etc.

53. In the case of diesel generators the annual cost comprises not only an allowance for depreciation, repair and maintenance, but also the running costs of fuel and lubricating oils.

Comparison of the costs of public electricity with alternatives

54. It follows then that these annual costs of alternative electricity sources can be compared with the annual cost of public electricity to determine which provides the cheapest source of power. The Sub-committee considered all 5 alternatives (para. 50) and concluded that, for sole genebank use, the 2 main alternatives with some potential for possible wide application in the near future were photovoltaics and diesel generators.

Photovoltaics

55. Photovoltaic cells (in which solar radiation is converted directly into electricity) may be a viable alternative to public electricity where the unit cost of the latter is very high.

56. The major factors to take into account at any proposed site for a photovoltaics system are:

(i) The insolation;

(ii) The efficiency of the photovoltaic system in converting the incoming solar energy into electricity;

(iii) The daily electricity requirement of the cold store (and, possibly, ancillary facilities); and

(iv) The unit cost of local public electricity.

57. Factors (i) and (ii) determine the daily power output per unit area of the photovoltaic cells. Factor (iii) divided by the daily power output of the photovoltaic cells per unit area gives the total area of cells required for the installation, which directly affects the total capital cost of the installation, and thus the annual allowance necessary for replacement (i.e. depreciation).

58. The daily electricity requirement of a store operating at the preferred conditions will be largely dependent upon ambient air temperature and the thickness of insulation, store size and design. Using the assumptions and equations provided in Appendix IX of Cromarty et al. (1982) a 100 m^3 store operating at -20°C in an ambient air temperature of 35°C would require roughly 21 kWh d^{-1} if the insulation were 200 mm thick.

59. Now, assuming that the insolation is roughly 6.3 kWh m^{-2} d^{-1} and the

photovoltaic system is 10% efficient then a 33-34 m^2 array of photovoltaic cells should be sufficient to provide 21 kWh d^{-1}. (These assumptions are thought to be applicable to climates in many developing countries.)

60. The initial capital cost of a 33-34 m^{-2} array, including batteries will be in the order of US$35 000. The photovoltaic cells are known to decline in efficiency as they age and are assumed to require replacement after 15 years. The batteries (approximately 30% of the initial cost of the system) will require replacing every 5 years or so. Thus the cost of a photovoltaic system is roughly US$56 000 over 15 years or roughly US$3 750 per annum, but this ignores inflation which may adversely affect the cost of imported technology.

61. Since the store requires 21 kWh d^{-1} it follows that a photovoltaic system is worthy of serious consideration if public electricity costs in the order of US$0.49 per kWh (since 0.49 x 21 x 365 = 3755.85).

62. Table 3 provides a summary of approximate values of power generated per unit area of array, area of an array required to generate 1 kWh d^{-1} and the depreciation cost per kWh for photovoltaic systems of differing efficiency under various levels of insolation. This table should not be used to decide whether a photovoltaic system should be installed. It is provided here only as a guide as to whether or not a more detailed evaluation of photovoltaic systems would be useful.

Diesel generators

63. In the majority of locations it is likely that public electricity will be cheaper than a genebank using its own diesel generators. Nevertheless, in any investigation of alternatives to public electricity it is worth calculating the cost of local generation of electricity using diesel generators. Appendix VI provides an example of such a calculation. If the costings appear favourable it would be advisable to check upon the availability and reliability of regular fuel supplies before proceeding.

Stand-by generator

64. Whichever method of supplying electricity is chosen, a stand-by diesel powered generator with sufficient fuel for 6 mo operation (see Cromarty et al., 1982) is also required in case of failure of the main power source.

ALTERNATIVES TO MECHANICAL REFRIGERATION

65. The preceding section considered alternative sources of electricity to public supplies for driving compressors in mechanical refrigeration systems. This section considers alternatives to mechanical refrigeration systems.

Thermoelectric cells

66. Electrical power (from any source) could also be used to provide cooling by using thermoelectric cells (also known as Peltier devices) in place of mechanical refrigeration systems. These are composed of 2 types of semiconductors connected alternately in series. Each connection between the 2 types of semiconductor provides either a hot or a cold junction when current is passed through the device. Thus heat flows from the cold junction (thereby providing refrigeration) to the hot junction - where the heat is dissipated. To ensure that refrigeration does occur at the cold end it is necessary to remove heat from the hot junction; water cooling systems are generally employed.

Table 3. Estimated power generated per unit area (kWh $m^{-2}d^{-1}$), area required to generate 1 kWh d^{-1} (m^2 $kWh^{-1}d^{-1}$) and depreciation cost kWh^{-1} (US$) for photovoltaic systems with differing efficiencies under various levels of insolation

	Photovoltaic System Efficiency								
	10%			12%			14%		
Insolation (kWh $m^{-2}d^{-1}$)	Power, kWh $m^{-2}d^{-1}$	Area, m^2 $kWh^{-1}d^{-1}$	Cost of kWh, US $	Power, kWh $m^{-2}d^{-1}$	Area, m^2 $kWh^{-1}d^{-1}$	Cost of kWh, US $	Power, kWh $m^{-2}d^{-1}$	Area, m^2 $kWh^{-1}d^{-1}$	Cost of kWh, US $
3.153 1/	0.3153	3.17	0.99	0.3784	2.64	0.82	0.4414	2.27	0.71
4.730 2/	0.473	2.11	0.66	0.5676	1.76	0.55	0.6622	1.51	0.47
6.305 3/	0.6305	1.59	0.49	0.7566	1.32	0.41	0.8827	1.13	0.35

1/ e.g. cloudy day
2/ e.g. partly cloudy day
3/ e.g. clear day

67. Since they employ no moving parts, Peltier devices are often said to be more reliable than mechanical refrigerations systems. However, in practical applications their ability to cool tends to be far less than expected. Moreover, the efficiency of thermoelectric cells declines as the difference between the cold and hot junction temperatures increases. They actually have a low thermal efficiency compared with mechanical refrigeration. Consequently they are not suitable for refrigerating cold stores at -18°C or thereabouts, since in this application the difference between the cold and hot junctions will be large.

Liquid nitrogen

68. Liquid nitrogen is a direct refrigerant, i.e. the liquid nitrogen is evaporated by absorbing heat and then lost to the atmosphere as gaseous nitrogen. It can be used as a backup or as the main refrigerant for a store operating at the preferred conditions. As a backup refrigeration system liquid nitrogen is unlikely to be economic due to the high cost of a holding tank (see Table 2). It is also unlikely to be used to provide the main refrigeration system for a conventional store because of the need to vent the store with air or oxygen before personnel can be allowed to enter the cold store (otherwise asphyxiation will occur).

69. The use of liquid nitrogen in vats to provide very low storage temperatures is, however, more promising. The economics are dependent upon high quality storage vats (which need to have very high insulation standards and to be manufactured for durability) and the availability and cost of liquid nitrogen, which both vary considerably according to location. Costings for genebanks producing their own liquid nitrogen or relying on commercial suppliers are provided in Table 2.

70. Storage of seeds for genetic resources conservation at, or close to, the temperature of liquid nitrogen is a promising technique but it is not at present endorsed for general application by the IBPGR Advisory Committee on Seed Storage.

71. A development programme at the National Seed Storage Laboratory, Fort Collins, USA, is well advanced, but identical procedures cannot be used for all species and some difficulties remain. Consequently it is envisaged that such stores would require a higher degree of management - at least when accessions are entered into storage - than stores operating at the preferred standards.

72. The potential advantage of liquid nitrogen storage is, however, that the subsequent monitoring and regeneration load may be very considerably reduced. For more information on seed storage in liquid nitrogen, see Stanwood (1984).

Absorption chillers

73. Absorption chillers can utilize heat generated by solar collectors to provide refrigeration. Their main advantage (in addition to independence from power supplies) is their lack of moving parts.

74. In the solid absorption-zeolite refrigerator, water vapour is driven out of a zeolite-filled solar collector during the day. The vapour condenses into water and is stored until the night. As the collector cools a vacuum results and the water in the system boils constantly at a temperature of 0°C or so; the evaporated water returns to the zeolite, but the remainder in the evaporator freezes (due to the latent heat required for evaporation) forming a block of ice which cools the chiller for several days. However, vapour transfer could be a problem in large commercial units, since it has not been actually tested on a commercial scale.

75. In the solid absorption-calcium chloride refrigerator, ammonia is driven out of a solar collector fitted with calcium chloride and cement. The ammonia is then condensed in a water tank-condenser and passes into an evaporator. At night the collector cools and pressure falls and the liquid ammonia in the evaporator boils at -12°C or thereabouts, the gas returns to the calcium chloride in the collector and ice is formed around the evaporator in the refrigerator.

76. The liquid absorption-ammonia refrigerator operates on a similar basis to the solid absorption-calcium chloride refrigerator, with the exception that the collector contains water with ammonia in solution as opposed to calcium chloride and cement with absorbed ammonia.

77. Absorption chillers are, however, being developed mainly for small-scale operations (refrigerators rather than cold stores) and will only cool a refrigerator down to between about 5°C and 10°C.

Radiation cooling

78. In a preceding section it was noted that building design can greatly influence store temperature. A special design, based on radiation cooling, employs clear night skies as a heat sink. The seed store design is then manipulated to maximize loss of heat energy from the store to this heat sink, with additional "ice" (water/alcohol mixture) storage to provide seasonal and diurnal storage of energy to maintain a stable low temperature. Obviously the design requires cold, clear nights to function and can therefore be considered to be of potential application in arid zones, particularly at high altitudes.

79. An Argentinian design for such a store is described in Appendix VII. This passive store, requiring no conventional power, is expected to operate at about -4°C and can be considered as a long-term store (although not meeting IBPGR preferred conditions).

80. However, although the principle is basically simple the design requires extensive simulation for each proposed site to estimate the performance of the building, and the store must be constructed carefully to comply with the design. The design appears to provide a solution to specific circumstances but is of limited application since there are comparatively few accessible areas where the design would be expected to function effectively. Moreover, the design and simulations so far remain untested in practice.

MAXIMIZING ACCESSION LONGEVITY WHERE RESOURCES ARE LIMITED

81. Cromarty et al. (1982) provided information on the design and engineering of long-term seed stores to operate at the preferred standards together with estimates of capital and running costs. In this section consideration is given to what should be done to provide the best possible storage facilities when the limited resources available are insufficient to provide a purpose-built long-term seed store.

Importance of seed drying and subsequent hermetic storage

82. Much can be done to increase longevity with comparatively little investment. From the earlier section, which compared the relative benefits of dessication and refrigeration, it should be apparent that desiccation and subsequent hermetic storage are of vital importance in any system and the most appropriate first step.

83. It is therefore imperative that, where resources are greatly limiting, some means is found of drying the seeds and that the seeds then be sealed in appropriate containers in order to maintain the low moisture content.

84. A basic system would include desiccators (or some other sealable container), a chemical desiccant such as indicating silica gel (but even toasted rice seeds could be used as the desiccant), a simple oven to regenerate the desiccant so that it can be used again, and sample bottles with good seals. The dried accessions can be sealed in the sample bottles and stored at ambient temperatures.

85. Obviously accession longevity will depend upon species, the initial quality of the seed, the moisture content to which the seeds have been dried, the reliability of the sealed container, and ambient temperature; but for good quality (i.e. high viability) accessions of species with good storage characteristics - such as the cereals, forage legumes and low oil content grain legumes - satisfactory storage for many years is feasible if they are dried to about 5% moisture content and hermetically stored at 10°C to 20°C.

Additional investment

86. Adequate drying and hermetic storage, therefore, should be considered as the first step. If slightly more resources are available, then the additional investment will depend somewhat on the material to be maintained. The alternatives are: either to improve the throughput of the drying system - by purchasing a low humidity, low temperature drying cabinet or room; or to reduce subsequent storage temperature - either by constructing a well insulated, passive store which maintains a store temperature below ambient, or by purchasing a chest-type deep-freeze cabinet.

Deep freeze cabinets

87. It cannot be emphasized enough that for small collections (or even medium-sized collections of small-seeded species) the purchase of 1, or perhaps several, deep-freeze cabinets is the next single most cost-effective step after seed drying and hermetic storage to improving accession longevity and reducing genebank workloads (provided the running costs can be met). See Table 2 and Ellis and Roberts (1982) for more information on deep-freeze cabinets.

Management of collections

88. It is necessary to emphasize that stores operating under less adequate conditions than the preferred standards can be successful, but require increased managerial skill. Essentially this entails making the most of the facilities available by providing the best storage conditions for the accessions most likely to deteriorate most rapidly.

89. The following examples highlight the actions which might be taken in circumstances where the preferred standards can only be provided for a minority of accessions (e.g. when only 1 deep-freeze cabinet is available), but where all accessions can be dried to about 5% moisture content and hermetically stored. The purpose of these suggestions is to minimize monitoring and regeneration activities, since these are costly, time-consuming, waste precious seeds and are not without risk.

90. In a genebank which maintains many species the accessions of those species with poor storage characteristics (such as the small-seeded vegetable species and high oil content grain legumes) would be selected for storage in the deep-freeze in preference to accessions of species with good storage characteristics.

91. If more space were available, then poorer quality (low initial viability) accessions of the species with good storage characteristics would also be selected for storage in the deep-freeze.

92. If insufficient room in the deep-freeze were available for all accessions of the species with poor storage characteristics then it is suggested that the larger-seeded of these species should not be stored in the deep-freeze (since many more accessions of the smaller-seeded species could be stored in a given volume).

93. In a genebank maintaining a single species it is suggested that the best storage conditions (deep-freeze cabinet at 5% moisture content) should be provided for the poorest quality accessions, i.e. those of lower initial viability.

94. Where a genebank functions as both a base collection and as an active collection and insufficient storage capacity is available at -18°C for all the material, it is suggested that each accession be divided into the base sample and the active sample and that the base samples be stored under the best conditions available.

COMPARISON OF DIFFERENT SEED STORAGE SYSTEMS

95. Table 2 provides a comparison of various aspects of different systems. One of the more surprising figures is the thirty-fold variation in running costs for purpose-built long-term stores.

Refrigeration versus insulation

96. Refrigeration entails removing heat energy from 1 location (e.g. the cold room) to another (e.g. the outside). Thus a refrigeration system acts as a "pump" and requires energy to act in this way. If a store were perfectly insulated from the ambient environment then the refrigeration system would only need to "pump" heat from the store initially; once the desired store temperature had been reached no more energy would be required.

97. No store is perfectly insulated, however, and the energy required to maintain the store temperature is proportional to the amount of heat energy entering from the outside and from electrical equipment such as lighting and air circulation fans within the cold room.

98. It follows, then, that the design and construction of the purpose-built seed store will greatly influence its running costs, since these factors influence the heat leak into the building and the ability of the refrigeration plant to dissipate heat.

Commercial cold store designs

99. In general a major constraint in the design of most commercial cold stores is to minimize the initial capital cost, because the intended life of the structure is short and running costs are comparatively unimportant (since the value of the material in store - e.g. meat - is very high). Commercial cold stores are also designed to operate at high relative humidities to minimize product weight losses. Genebank cold stores, in contrast, should be designed for a long life at low running costs, and in some cases for low relative humidities. It follows, then, that the standard commercial cold store designs are not the most appropriate for genebanks. Unfortunately many designers have failed to recognize this.

Disparities between running costs of different cold stores

100. Appendix IX of Cromarty et al. (1982) provides equations to estimate the running

costs of cold stores. In particular these equations can be used to demonstrate the influence of different standards of insulation on running costs.

101. The lower figure in Table 2 is for annual average running costs of a well-designed, well-constructed, well-insulated store operating in temperate environments which, because of good management, is accessed at only infrequent intervals. The upper figure in Table 2 is for the maximum running costs of a poorly-designed, poorly-insulated store operating in tropical environments which is accessed at frequent intervals (and consequently requires a dehumidified air lock) which increases running costs. Frequently accessed stores also entail a heavy 'human workload', i.e. body heat increases the refrigeration load.

102. The lower figure represents an 'ideal' which can be, but is rarely, achieved in practice. The upper figure illustrates the false economies of using standard commercial designs which do not meet the design criteria suggested by Cromarty et al. (1982) combined with poor management practices.

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APPENDIX I

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APPENDIX II

AGENDA OF THE MEETING OF THE IBPGR SUB-COMMITTEE ON COST-EFFECTIVE LONG-TERM SEED STORAGE 1 - 3 APRIL 1985

1. Potential of hermetic storage of very low moisture content seed accessions to avoid or reduce the refrigeration requirement.

2. Areas where natural conditions may be suitable for long-term seed storage.

3. Potential of alternative energy to reduce the costs of operating genebanks.

4. Improvements to existing cold stores to reduce costs.

5. Recommendations.

APPENDIX III

COMPARING POTENTIAL AMBIENT SEED STORE SITES WHERE SEED TEMPERATURE FLUCTUATES

1. Seed bulks are largely self-insulating and consequently the temperature of seeds in store will not vary as greatly as the air temperature within a fluctuating temperature store. Nevertheless, where a seasonal trend in temperature within the store occurs, seed temperature will change but lag behind the seasonal change in air temperature. When comparing 2 or more different sites for a seed store in which temperature is not controlled it is common to compare temperatures between the sites by determining the annual mean seed temperature for each location.

2. It is not correct, however, to assume that the rate of deterioration in a storage environment where temperature fluctuates is a function of the annual mean seed temperature. Mean seed temperature would only be appropriate if the relationship between temperature and seed longevity (at a constant moisture content) were linear, but - as has already been discussed - it is not; it is approximately semi-logarithmic. For this reason for seed storage it is necessary to describe a fluctuating temperature regime not by the mean seed temperature but by an "effective" seed temperature. The following equation (from Roberts, 1961) can be used to describe the "effective" seed temperature (T_E) of a fluctuating temperature storage regime:

$$T_E = \log (\Sigma [\text{antilog} (tC_2) \times w]/100) / C_2$$

where t = recorded seed temperature in °C, w = the percentage of time the seeds spend at each temperature t, and C_2 is a constant. The term C_2 was originally derived for a simple viability equation in which the relationship between temperature and seed longevity was thought to be semi-logarithmic. Although it is now known that the term C_2 cannot be used over wide ranges of temperature, for narrow, specified, temperature ranges over the ambient temperature range a value of C_2 can be provided for the above equation which will not result in detectable error. Table 4 provides values of the constant C_2 appropriate for different temperature ranges.

3. Applying the above equation to different regimes in which seed temperature fluctuates throughout the year highlights an important aspect of such regimes on "effective" temperature, and thus seed longevity. The greater the amplitude of the alternation the higher is the effective temperature above the mean. This is because of the exposure to the relatively more deleterious higher seed temperatures if the amplitude is greater. Thus any attempt to damp temperature alternations by adjusting the design of ambient seed stores will be of considerable benefit to seed longevity in ambient stores if seasonal variation in seed temperature is great.

Table 4. Values of the constant C_2 to be applied to determine 'effective' temperatures of stores with fluctuating temperatures

Lower Temperature	Upper temperature (°C)					
	-10	0	10	20	30	40
-20	0.027	0.031	0.036	0.04	0.043	0.049
-10	-	0.036	0.04	0.043	0.049	0.053
0	-	-	0.043	0.049	0.053	0.057
10	-	-	-	0.053	0.057	0.061
20	-	-	-	-	0.061	0.066
30	-	-	-	-	-	0.07

APPENDIX IV

THE SEED SECURITY STORE OF THE NORDIC GENE BANK

The site

1. The site of the seed security store in Svalbard, Norway (the approximate latitude and longitude are 78°N and 15°E respectively) is passage AT2 in mine 3 of the Store Norske Spitsbergen Kulkompani (SNSK). The entrance to this mine is 3 km west of Longyearbyen, but only 1 km from the airport of Longyearbyen, and 200 m above sea level. The passage AT2 is located 285 m from the entrance to the mine and is separated from the main passage by a wooden wall. The gallery in which the store is sited is about 19 m in length by 4 m high by 4 m wide and encased in a load bearing frame to prevent rock falls. Coal was mined from this gallery until about 10 years ago. The rock overlay is about 70 m.

Ambient environment

2. Air and rock temperatures within passage AT2 are very stable at -3.7°C to -3.6°C and -3.8°C to -3.7°C respectively. Relative humidity appears to be very stable at about 90%.

The store

3. A steel (double pickled steel 42) container measuring 4000 x 1600 x 2000 mm has been positioned in passage AT2 to provide the seed store. Before use the steel container was sandblasted and the following anti-corrosion treatments then applied: (1) 60-80 microns zinc silicate (Galvanosil 1570); (2) 4 separate applications of 125 microns tar epoxy (Hempadur Rar 1513).

4. The container is also electrically isolated from the ground. The cost of the container including the detailed corrosion protection was US$13 000.

Accession containers

5. The seed accessions, after drying, are sealed in pyrex glass ampoules, labelled and the accession number also engraved on the ampoule. After an intermediate period of storage at -20°C several accessions and a copy of all relevant information are packed into a wooden box 500 x 250 x 250 mm at Alnarp and then despatched to Svalbard by air within 50 mm thick foam plastic filled with solid carbon dioxide ('dry ice'). On arrival at the mine the wooden boxes are stacked in the store. The average cost per 500-seed accession of ampoules, wooden boxes, etc. is between US$1 and 2.

Inspection

6. The container, gallery and access route are checked monthly (by SNSK). The initial monitoring interval of accession viability in the store will be 2.5 years.

APPENDIX V

THE AMBIENT SEED STORE, QINGHAI, CHINA

Location

1. The site of this ambient temperature seed store operated by the Qinghai Academy of Agricultural Sciences Xining, is Qinghai, China, 2295 m above sea level, at an approximate latitude and longitude of 37°N and 102°E.

Ambient environment

2. Annual mean internal and external temperatures are 9.7°C and 12.5°C respectively. Maximum internal temperature is 21.8°C. Annual rainfall is 430 mm.

Accession containers

3. After drying accessions are packed and sealed in steel trunks.

Seed longevity

4. Examples of reported seed storage life are no obvious decrease in the germination of pea and faba bean seeds after 11 and 15 years respectively, and 68% germination in wheat after 16 years storage.

APPENDIX VI

AUTONOMOUS ELECTRICITY SUPPLIES USING DIESEL GENERATORS

1. In countries where the unit cost of public electricity is very high it may be useful to compare unit electricity costs of the public supply with the cost of autonomous generation of electricity using a diesel generator set. The cost of generating electricity from a diesel generator comprises the cost of diesel fuel, the maintenance cost of the generator set, and the depreciation cost of the generator set which will allow the set to be replaced when it is no longer reliable.

Fuel cost

2. The cost of diesel fuel per unit of electricity generated will be the product of the cost of fuel (e.g. US$ per litre) and the fuel consumption per unit of electricity generated (e.g. litres per kWh). Fuel consumption will be largely dependent upon the design (and size) of the generator set, the maintenance status of the set, and electrical load. As an example a generator set capable of generating 15 kWh in continuous operation (but see below) in a tropical climate of 40°C no more than 750 m above sea level typically consumes 0.453 litres of fuel per kWh generated.

Maintenance cost

3. No generator set will run continuously. Occasionally the set must be closed down and maintenance carried out. This disruption to the power supply will pose no problem for the cold store since its high mass and good insulation will enable it to maintain the store temperature for several hours (see the information on the thermal time constant of cold stores in Cromarty et al., 1982); but in any case the stand-by generator (para. 64) can be operated whilst the main set is undergoing maintenance. A typical example of maintenance frequency requirement is given below.

4. The 15 kWh set discussed above is designed for 1000 h continuous operation. After this period the engine must be stopped, the lubricating oil changed, the diesel injectors checked and, possibly, cleaned and new fuel and oil filters fitted. In addition after every 2500 h of operation additional components must be checked and/or replaced. This means that each year the generator set will require servicing about 10 times. A minimum estimate of materials for these services would be about US$360 per year (but the servicing costs could be very much higher than this).

Depreciation cost

5. The life of a generator set will be dependent upon the hours of operation per year, the operating environment and the standard of maintenance. With regular servicing the set described above has a life expectancy of 5 years in continuous operation. The initial cost of such a set is US$10 200, and thus the annual cost of depreciation will be in the order of US$2040.

Comparison of unit costs of public and autonomously-generated electricity

6. Before the unit cost of autonomously-generated electricity can be calculated it is necessary to determine maintenance and depreciation costs per kWh of electricity generated. The annual cost of both of these is US$2400. Assuming 365 d operation per year and 300 kWh generated per day then the combined maintenance and depreciation cost is US$0.022 kWh^{-1}.

7. In the UK the cost of diesel oil is US$0.276 litre^{-1}. Since fuel consumption is 0.453 litre kWh^{-1}, the unit cost of fuel (using UK fuel prices) would be US$0.125 kWh^{-1}.

8. Combining these 2 elements of costs we see that the unit cost of autonomously-generated electricity is US$0.147 kWh^{-1}. This compares with a public supply cost in the UK of US$0.074 kWh^{-1}. Clearly in this example the public supply is considerably cheaper but elsewhere the situation may be different. Unit costs of public electricity and fuel prices vary greatly throughout the world. Accordingly a method of comparison for a range of costs is presented here (Fig. 3). Fig. 3 provides an initial method of comparing local costs of the public supply and diesel fuel to determine whether a more detailed investigation is worthwhile. The dividing line shown assumes a fuel consumption of 0.453 litre kWh^{-1} and a depreciation and maintenance cost of US$0.022 kWh^{-1}. Of course if different estimates of fuel consumption were used (i.e. for a different generating set) a different dividing line should be constructed.

Specification of a diesel generator

9. If it is decided to purchase and install a diesel generator, it is vital to specify clearly the proposed use of the generator. For example, it is important to specify that the generator is for automatic, continuous operation and to give details of the ambient environment. The set should be capable of shutting down automatically in the event of faults and additional silencing and fire prevention devices may be required. Most sets only have sufficient fuel capacity for 24 h of operation. Consequently an automatic system of transferring fuel from a separate bulk fuel tank to the generator is required. This bulk fuel tank should be isolated from the generator set and well away from the genebank to reduce the risk of fire. Finally, a large lubricating oil tank will be required for continuous operation.

APPENDIX VII

SUMMARY OF THE DESIGN OF THE PROPOSED PASSIVE SEED STORE AT ABRA PAMPA, ARGENTINA, TO UTILIZE RADIATION COOLING

The site

1. The site of the proposed store is Abra Pampa in the Argentinian Puna at an altitude of 3500 m and latitude 22° 30' S.

Ambient environment

2. The site is located in a cold, arid zone where cold, cloudless nights mean that the sky can act as a very effective heat sink. The mean annual temperature of the site is 7.0°C with mean monthly temperatures varying from 0.0°C to 12.5°C. The annual mean minimum temperature is -3.9°C and mean monthly minimums range from -14.2°C to 5.3°C. The annual mean night sky temperature is -21.4°C with mean monthly night sky temperatures ranging from -32.1°C to -11.4°C. The annual mean global radiation is 23.4 MJ m^{-2} d^{-1} with mean monthly values varying between 17.5 and 29.4 MJ m^{-2} d^{-1}. Annual mean relative humidity is 49% with mean monthly values varying between 34% and 67%.

The store

3. Fig. 4 provides an outline of the design of the proposed store. No power supply is provided to cool the store. Instead cooling occurs during the night by radiative cooling through the roof to the clear, cold night sky. Convection currents within the store at night ensure that the cooled air near the roof flows downwards, is then replaced by warmer, less dense air which in turn is cooled. During the day, when the roof is hotter, the air is stratified and forms an insulating layer. The roof of the seed storage chamber (expanded polystyrene) insulates the cold store from this hot air. In the summer, night sky temperatures are not cold enough to contribute sufficient radiative cooling to maintain the store at a low temperature. Consequently ice is made during the winter in the bottles containing the water/alcohol (12% alcohol) mixture (freezing point -6°C) to provide additional cooling in the summer. The thick (400 mm) adobe walls are necessary to minimize temperature rise during the day and to damp fluctuations in the temperature within the store. It is assumed that both roof and walls will be painted white to minimize heat gain from insolation.

4. Since both cooling and insulation are dependent upon air currents resulting from very small differences in air pressure, special precautions are required to avoid air infiltration into the store, and the success of the store will be dependent upon meticulous construction. The cost of a basic 40 m^3 store without shelving etc. is estimated at US$20 000 at 1983 prices, but the cost is likely to vary greatly according to local costs. Simulations suggest that, at the location described above, store temperature will vary between -5°C and -3°C throughout the year; that is about 10°C to 12°C below the annual mean temperature.

5. This design is of potential application in regions with climates similar to Abra Pampa, but each site will require extensive monitoring of the climate together with detailed simulation of store designs in these environments. Prof. G. Lesina (address in Appendix I) has generously offered to help with these simulations and should be contacted for further assistance. It should be emphasized that a seed store has not yet been constructed to this design. Consequently it is not yet known whether the cold store temperature of -4°C will be achieved in practice.

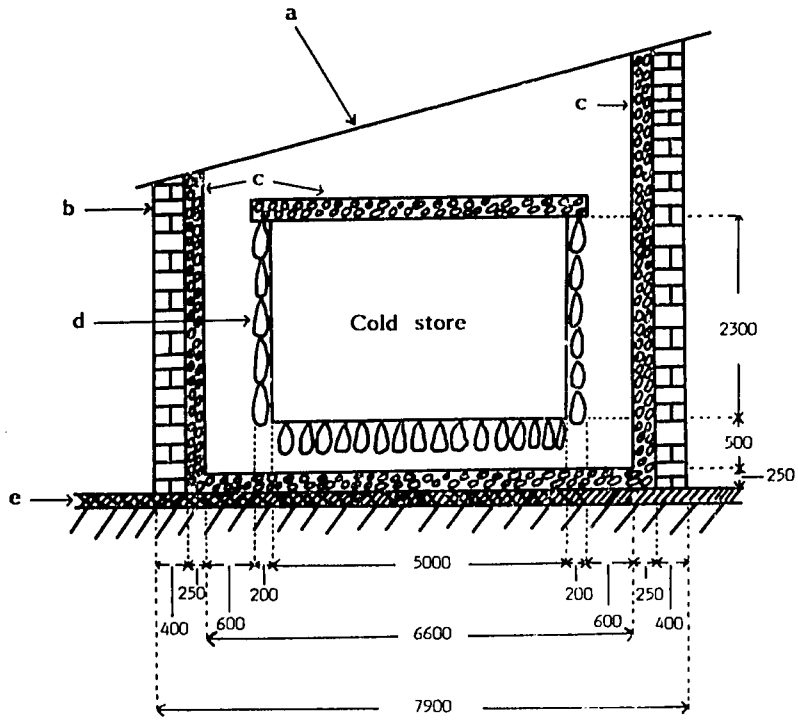

Fig. 4. Illustration of the basic features of a passive seed store designed to employ radiative cooling by L. Saravia and G. Lesina, (Instituto de Energia no Convencional (INENCO), Argentina) showing: (a) radiant roof of 15°C slope facing south (in southern hemisphere, but north in northern hemisphere) and constructed from corrugated aluminium sheet painted white; (b) adobe wall painted white; (c) expanded polystyrene insulating external walls and floor and the cold store roof; (d) lenticular-shaped polythylene bottles each containing 3 kg of an alcohol/water mixture (12%); and (e) sub-floor constructed from wood. All dimensions given are in millimetres.