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Multinational repositories (MNRs) highlight the need for transnational information management in geological disposal

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Multinational geological repositories (Multinational repositories: MNRs) will inevitably be features of the international radioactive waste management landscape in future decades. They will involve more complex requirements for long-term information management than national deep geological repositories (DGRs) but the considerations involved in managing these requirements also point to wider needs for transnational information management for any country with a national deep geological repository. This article looks at what information needs to be propagated into the future for both DGRs and MNRs, and for how long. It is argued that the critical requirements are quite limited and are readily achievable, with the most important period being the coming few hundred years. The transience of organisations and national boundaries, issues being addressed for MNRs, also affect any national programme, but are generally overlooked. It is concluded that there is a need to move towards international oversight of all geological disposal facilities, including a common system of regulations and information archiving, and that providing these is a potential role for the IAEA.

KEYWORDS

multinational repositories, information management, deep geological repository, international oversight, long-term

1 The inevitability of MNRs

Is waste disposal the last barrier to acceptance of nuclear power? Will slow progress in disposal stand in the way of the new global enthusiasm for advanced reactors and small modular reactors (SMRs)? For decades, opposition to nuclear power has cycled around arguments related to reactor safety, costs of nuclear electricity, and the feasibility of safe disposal of wastes. In fact, safety levels have always been high and are still improving and the life cycle costs of nuclear power are not a major obstacle. However, the so-called "unsolved waste disposal problem" is still put forward by some objectors to nuclear power. This assertion is unfounded. Today, it is universally acknowledged that disposal in deep, stable geological formations can provide a permanent safe solution. Intensive studies of the safety of mined repositories have confirmed the achievable safety levels and, importantly, facilities of this type are currently being planned, licensed and constructed in major mature nuclear programmes, e.g., in Finland, Sweden, France, Switzerland and Canada (INTERNATIONAL ATOMIC ENERGY AGENCY, 2022).

In any country hosting a deep geological repository (DGR), the facility must be designed and sited in a manner guaranteed to ensure the safety and security of present and future generations. However, implementation of a state-of-the-art DGR requires a major input of financial and personnel resources, accessibility of suitable siting regions and management of the socio-political challenges that have often arisen in national radioactive waste management programmes. This can present major problems in countries with limited numbers of nuclear power plants (and thus reduced DGR funders), or with no nuclear power but long-lived wastes from other nuclear energy applications. One solution to this is for countries to cooperate in implementing a multinational repository (MNR)—a facility in one host country that accepts wastes for disposal from a number of user countries. An MNR, chosen for objective reasons independent of political borders, can optimise the benefits for all, as illustrated in the Table below.

openness and the transfer of sometimes sensitive information to an entity outside the national boundaries. In the last 20 years, there has been much work on knowledge preservation within DGR projects but, although there has been sharing of R&D results in the scope of numerous joint research programmes, little has been said about strategic and project-based knowledge transfer between countries facing similar programme challenges at the back-end of the fuel cycle. The more advanced DGR programmes are certainly willing to share freely some of their knowledge with less advanced projects, but a formalised system that would require critical information to be shared with foreign partner nations, also needs to be considered. Such transfers would overlap with the requirements of an MNR project.

In this article we explore whether the inevitable advent of regional and/or globally linked MNRs will bring specific requirements for information transfer, storage and archiving to those involved, and whether interactions between MNR partners could be a model for how national DGR programmes might interact. We begin by looking at the nature of the knowledge propagation that is needed for any DGR project.

A valuable service to countries with:	A valuable asset for countries with:
• modest size nuclear power programmes	• suitable geological and environmental conditions
• plans to introduce nuclear power	• ability to provide high-tech infrastructure
• no nuclear power - but long-lived wastes	• interest in economic development
• small areas, complex geological environments	• remote, low population areas
• limited financial resources	• a stable political system
• interest in economic optimisation	• the trust of the international community
• commitment to global security and non-proliferation	• commitment to global security and non-proliferation

If nuclear power is to be implemented or expanded in the increasing number of countries adopting such policies, then global safety and security will depend on all of these having access to a national DGR or to an MNR. In our view, MNR projects will become common over the next 20–50 years. They might result from a shared, partnering concept between countries (even just two countries) or from an offer from a qualified nation to provide a commercial disposal service to many other countries. Most work on MNR concept development has been done on the former approach. However, the current high interest in the development of SMRs, which can be produced in factories and implemented around the world in large numbers, may well lead to intensified international cooperation that will favour other MNR solutions. A supplier country producing an extended series of SMRs may be more likely to "take back" the resulting spent fuel, or the emergence of a global network of SMRs may result in a service provider taking advantage of this market opportunity for a MNR.

Participation in an MNR project requires a high level of mutual trust among the players involved, and this in turn will require the willingness to share knowledge and information (as well as costs). Some of the data involved might, in the case of a solely national programme, have been regarded as proprietary commercial material, but an MNR option will require full transparency. Confidence building between MNR partners is, in some aspects, akin to confidence in safeguards procedures, which also require

2 DGR implementation: knowledge and data requirements

Knowledge preservation and transfer are universally considered to be essential objectives for any DGR programme. We consider two time periods in this article:

- Pre-closure: covering all activities from radioactive waste management (RWM) project inception to final closure of a DGR.
- Post-closure: beginning with any period of institutional presence to control the site and then extending indefinitely into the future.

2.1 Pre-closure knowledge management

Given the multi-decade timescales in DGR programmes from initiation through implementation, operation and final closure, there is an obvious practical need to relay working information forward in time. Staff in waste management organisations (WMOs) or regulatory agencies move on or retire, lessons learned from successes or failures must be preserved, new technologies may be adopted. Information management during the long development period of a DGR is a highly dynamic matter, requiring day-to-day actions and an approach that can essentially frame the manner by which a whole project is managed. Today, there are many tools and mechanisms to ensure that this knowledge generation, collation, distribution, utilisation, transfer and retention occurs effectively, and we do not aim to review these here. At this point we simply note that this dynamic pre-closure handling of information contrasts completely with the almost static requirements for post-closure data management discussed in the next section.

DGR projects are managerially complex, last decades, generate vast amounts of electronic and paper records, and involve many individuals and organisations. The more complex and extensive the waste inventory, the greater are the volumes of data that will be generated. The amount of information generated over this time is potentially (and in reality, for some countries) immense. For example, the U.S. Nuclear Regulatory Commission's Licensing Support Network (LSN, 2021) for the proposed DGR at Yucca Mountain contained more than a million documents in the early 2000s.

The authors of this article began working on DGR projects more than 45 years ago—two generations back. Already, records of much of the work that we were involved in during the 1970s and 1980s have become hard to trace or have simply evaporated. That has happened for a number of reasons: little or no attempt was made to centralise and retain the information; record keeping media have changed (multiple times for IT data storage technology); the concept of libraries with shelves of documents and reports is essentially gone, and many, even flagship, institutions have closed their libraries, without complete transfer to electronic media. The passage of information from those times on to the next two generations is thus already, and will become increasingly, patchy. Often, the only information we have is about *what* was done, with nothing about *why* it was done, or why it was done in a particular way. Importantly, while successes are often documented, failures or blind alleys are often retained only in the human memory of those who were present. Of course, even for the short period of the authors' own working experience, the relevance and consequent value of much 'old' information has been superseded by more technically advanced and more focussed work, so the loss of some information is not always critical.

Because knowledge management was not a priority matter some decades ago, what can be found in archives today too often tends to be random items rather than information collated and structured specifically for future reference. There are of course exceptions, such as the Yucca Mountain Digital Database (OSTI, 1992), a digital geographical database of geoscience-related characteristics of the proposed repository site that was created in 1992 to provide the US Nuclear Regulatory Commission with a visual perspective of geological, geophysical, and hydrological features at the Yucca Mountain site.

Even within a purely national DGR programme, it will be difficult to assure information preservation and transfer between the organisations involved. Most (but not all) DGR projects are managed by government agencies or quangos and regulated by government authorities. Responsibilities and organisational structures change frequently. In the United Kingdom, for example, the responsible government ministries have changed name and structure four times in 40 years and the WMO has changed name, structure and "ownership" three times. At least two organisations are directly involved in regulation (the Office of Nuclear Regulation and the Environment Agency). In addition, other agencies with specific RWM advisory or review responsibilities related to DGR development have come and gone. The UK DGR project is expected to run well into the 2100s, with continued change being inevitable. Ensuring that the knowledge "parcel is passed" will be a critical activity and must involve regulatory oversight. As discussed in Section 3, the implications when more than one DGR user country is involved will need specific management arrangements to be made.

A critical aspect of the dynamic pre-closure information management systems mentioned above is the ability to address the changing requirements that are inevitable during the lifetime of a project. Not least among these changes are likely to be changes in the "external" boundary conditions driving the project, such as an evolving waste inventory as nuclear power and RWM technologies advance, as NPP lifetimes extend, as new facilities come on line and as national energy and RWM policy adapts. Change management requires the assumptions, drivers and support data used in decision-making to be transparent and properly recorded. Again, there are clearly additional challenges when compounding more than one set of national boundary conditions when a MNR project is being developed, and these are discussed further below.

2.2 Post-closure knowledge management

For post-closure information preservation and availability—effectively after a DGR project is terminated and the responsibility has inevitably devolved to the state—periods of many thousands of years are often spoken of. We begin by considering whether there is, in fact, only a limited set of information that needs to be projected into the future, what the objectives of doing this are, and the likelihood that we will be successful in achieving them.

Once all activities have ceased at any DGR location (other than monitoring and surveillance, for whatever duration is agreed on), continued access to information is essential, in order to:

- Prevent inadvertent intrusion or other activities in the vicinity that could challenge isolation and jeopardise containment;
- Facilitate surveillance over fissile materials to satisfy nuclear safeguards;
- Allow any transfer of liabilities to be assessed if political responsibility for the location changes;
- Facilitate removal of materials if re-use becomes beneficial;
- Facilitate mitigation actions in the unlikely circumstances that the system fails to contain the wastes adequately.

This information needs to be available to both national and international organisations. Currently, for a national DGR, only the second item needs to be available to international organisations. Owing to the transience of all organisations over decadal timescales (and the transience of national boundaries, discussed further later), ideally this information ought to be openly accessible to assure propagation into the future. However, some of the information could represent a potential security risk: for example, the exact nature and specific locations of fissile materials or of valuable resources that could encourage bad actors to intrude. This safeguards issue will be difficult to resolve. Certainly, it would be expected that a DGR close to a current national border would share information with relevant organisations in a neighbouring country. Even for a solely national DGR, it can be seen that multi-national ramifications for data management begin to emerge. These are discussed further in Section 3.

To meet the above objectives, the principal information about DGRs that requires sustained propagation into the future concerns:

- Knowledge of location;
- Details of the facility design and materials, and how it was constructed, operated and closed;
- Knowledge of the waste materials inventory and the exact spatial disposition of packages;
- Details of how post-closure behaviour was expected to evolve and how safety is being provided by the DGR system, as detailed in the safety case that was used for licensing;
- A record of environmental monitoring data going back to the pre-construction period.

This comprises only a small amount of critical information: the essentials, allowing the objectives listed above to be met, probably amount to a few terabytes of data.

How likely are we to achieve long-term preservation of this information and for how long do we need to ensure that it is actually preserved? One way to look at how, and how successfully, we might manage information over very long periods is to work backwards and look at what we still know about major engineering developments and construction projects over the last 1,000 years—a period that covers 40 to 50 generations and for which useful records have been preserved, with varying degrees of success. If we move back prior to this time, we enter a period where any extant material that was originally intended to form a record for future generations diminishes rapidly. As an example, for context, if the Doomsday Book record of land ownership in England, prepared for King William I in the 1080s, had included details of the owners and location of a waste repository, we would still have that record, 1,000 years later, but in a form and a language style that has limited meaning today. Going back 1,000 years, we know only about the drivers of some key historical events—we can only guess about the decision-making processes and supporting data that lie behind the siting and construction of the mediaeval castles, palaces, bridges and Renaissance infrastructure that still stands across Europe. Why here and not there; why not bigger or smaller; why this design, not that? Again, we have the "what", but we do not know the "why".

Even if we step back a much shorter time, to 100 years, any historian will confirm that lack of records or patchy preservation, for the reasons mentioned above plus the ravages of wars and radical changes of national governance, make it difficult to be certain about how and why key political, technical or societal decisions were taken in the past. "Lost" environmental hazards created in the last few hundred years (even the past 50–100 years) are still being discovered today: plague pits, unfilled mineshafts, toxic waste dumps (OECD Nuclear Energy Agency, 2014).

One thousand years is also a critical technical period for maintaining isolation and containment in a DGR, during which a considerable decline in radiotoxicity and heat output of high-level waste (HLW) or spent nuclear fuel (SNF) will have occurred. If the DGR were to be interfered with during the period over which it is evolving to the "steady" initial state that is the starting point of post-closure safety concepts, then its performance could be affected. A DGR for HLW or SNF will be progressively re-saturating and responding to the early heat pulse over this time. Yet this is arguably the most likely period in which it might be accessed. Fast-paced technological developments may make the materials it contains attractive and more easily retrievable, and cultural and historic curiosity about an intriguing, buried artefact is likely to be strong. This may mean that intrusion into a DGR is more likely to occur in the next 100 years than at any subsequent time. Any such deliberate intrusion would make use of preserved information about the characteristics of the facility. After a thousand years, and certainly after the hundreds of thousands of years for which safety assessments are carried out, there are no plausible human-caused disruptive events that could lead to catastrophic consequences, or even significant risks to humans or the environment.

The conclusions so far, for any DGR, in any country, are thus that:

- Only a relatively small amount of information is required to ensure that inadvertent intrusion to a DGR is avoidable or that advertent intrusion can be safe;
- We ought to be able to preserve and propagate the essential and critical information effectively for at least some hundreds of years; ensuring preservation for these next few hundred years is thus the most important objective;
- Although addressing the much longer time horizon should not be forgotten, the technical design of the repository and the characteristics of the wastes imply that, certainly after 1,000 years, intrusion into the DGR, disruption of the facility or releases to the surface of significant quantities of radionuclides, are all unlikely occurrences—and none of these leads to major impacts on humans or the environment;
- Assuring the availability and ready accessibility of information to an ever-changing spectrum of national stakeholders is essential, even for a national DGR, and requires regulatory oversight;
- It will also be essential to make information available on a trans-national basis, and this will both raise and, sometimes, answer security concerns for some waste materials.

How then might these conclusions change if we were dealing with a multinational DGR?

3 The specific requirements of an MNR

There are several unique features of an MNR that, compared to a national DGR, add to the requirements for information transfer and propagation nationally, between participating user organisations, between agencies in the countries involved in the project and between international organisations (e.g., overseeing safeguards). These features can be related to the technical, governance, financing and liability characteristics of an MNR project.

3.1 Technical characteristics

The waste inventory, waste types, the conditioning technologies and the packaging characteristics can be expected to become increasingly complex with an increasing number of MNR participants. Although there will certainly be a drive towards developing common and standardised packaging for disposal, the historic nature of some waste streams will mean that harmonised solutions could be challenging to achieve. An MNR for a group of "newcomer" nuclear power countries would need to broaden its design concept if the project were to be joined by a country with an extensive inventory of legacy wastes. In addition, the potential for an increasingly broad choice of NPP technologies, as advanced reactors come into use in the form of SMRs, will add to the diversity of SNF and decommissioning waste types. Despite the potential range of options to accommodate these materials, an optimised MNR will aim for only a few different engineered design and emplacement concepts for its disposal vaults/tunnels/boreholes, into which all the wastes from several user countries will be fitted.

A key issue here is to ensure that information on the diverse nature of the MNR inventory is propagated in a common format and to a common level of detail. Information on legacy wastes from different user countries is expected to be of variable quality, gathered using different techniques and recorded in multiple languages and media forms. There will consequently be a requirement to assess the necessary level of detail of pre-disposal waste characterisation and harmonise the systems used to gather and record the data. Countries using an MNR will have to work closely together to achieve this. The basis for this must be a unified system of waste acceptance criteria (WAC) and a versatile approach to compliance testing, all of which must be agreed by the participating countries and adhered to by later joiners. The level of openness and information transfer required clearly goes beyond that needed in national DGR programmes.

The passage of time will bring inevitable changes to a complex DGR/MNR project. Some national DGR facilities are already planned to function for a century or more—timescales during which huge technological developments may take place. One hundred years ago, we knew nothing about nuclear fission as a source of energy and most Europeans and North Americans lived in dwellings with no electricity supply. Even as recently as 1933, Ernest Rutherford observed that *"The energy produced by the breaking down of the atom is a very poor kind of thing. Anyone who expects a source of power from the transformation of these atoms is talking moonshine* (Associated Press, 1933)*."* We must expect major changes in the technologies and the drivers for a geological disposal facility.

Even were things to function as they do today, we can already see that an MNR project will bring significant logistical challenges owing to the relative times and rates of waste arisings from the different user countries. This will give rise to complicated scheduling for transport and emplacement, and the more participants that are involved, the more extended the timetable for disposal might become. Established nuclear programmes might have wastes that have already cooled for decades and hence are ready for disposal in a DGR; new nuclear programmes will have no such wastes for 40 years or more. The ability to move nuclear materials across national borders and through international waters and airspace to service an MNR will require both the availability and the control of information. It can be expected that the practical and legal aspects of this will change, as discussed below.

3.2 Governance characteristics

There are many ways that an MNR project might be governed. Each of the options for the following components of governance could be matched up with any of the other component options, producing a broad array of possibilities.

The **implementer** of an MNR might be:

a. The national WMO in the host country
b. A multinational organisation based in the host country
c. A multinational organisation based outside the host country
d. An international organisation, such as the IAEA

The **owner** of an MNR might be:

1. The government of the host country
2. The shareholders of the national WMO in the host country
3. The WMOs or the waste producers of the user countries
4. The governments of the user countries
5. A non-profit international company representing any of the above
6. An international commercial company

The **regulator** of an MNR might be:

i. The national regulatory agency (or agencies) in the host country (international commitments make this obligatory)
ii. A consortium of the national regulators in the user countries
iii. An international organisation
iv. Any or all of the above, working together.

Of the various possible combinations of implementer-owner-regulator, some are more likely arrangements than others. For example, current developments in Europe (promoted by the ERDO Association) could move in the direction of a *b-2-ii* combination. Conversely, at present, a *b-6-iii* combination seems an unlikely development. However, in all cases it is expected that an MNR project would necessitate many organisations working together and, although these organisations are likely to have variable levels of competence and commitment to the project, they must be able to share knowledge and data.

For any DGR, the IAEA Joint Convention (IAEA, 1997) requires the creation of a structured framework defining the roles of all relevant entities—regulators, implementers, national governments, local communities, supranational organisations, etc. When a group of potential participants in a formalised MNR is established, then explicit negotiations on legal responsibilities and liabilities will be an immediate top priority. These negotiations will require participation of technical, legal and financial experts from the partnering organisations, all with critical requirements for shared information.

In any country, the level of knowledge, expertise and competence in geological disposal will depend on the history of national DGR development. Some countries will have extensive experience and knowledge, while others will be able to bring relatively little to the table. The combinations of possibilities are again wide. For a host country that has had an active DGR programme, the national WMO would have high levels of competence across the board, Nevertheless, even a country with no such history and only wishing to use an MNR as a service should have, or should develop, an “informed customer” level of competence. This will be necessary to inform a national government’s decision making on participation and enable it to respond competently to political and public questioning of the decisions. Knowledge transfer is consequently likely to be a major activity requiring dedicated efforts on all sides, and require special arrangements with respect to sensitive information.

In a national DGR programme, the national policy and regulations on nuclear power can alter the technical and financial boundary conditions: for example, by increasing or decreasing the numbers of NPPs planned, or changing the requirements on monitoring or retrievability. But the MNR implementer has to satisfy the demands of all user countries, which will be a more challenging task. At a more detailed level, the safety authorities of user countries may agree to the transfer of wastes only if the MNR would also satisfy their national requirements. The United States and Switzerland are examples of countries with this type of requirement (Kegel and McCombie, 2022). This implies that an MNR may have to satisfy the regulatory requirements of the strictest regulator amongst the users.

One approach to this is to harmonise regulatory standards and management requirements across the user countries. This might require changes that reach as far back as national policy amendments (e.g., user countries might have different legally embedded policies on waste retrievability). Deciding how to manage compliance with multiple national policy and regulatory requirements, and how far to modify these, will be a challenging task. However, harmonisation and the adoption of widely agreed standards and requirements would seem to be a generally beneficial development that ought to simplify international and/or regional radioactive waste management. It would also facilitate the transfer of information to future generations.

Within this complex panoply of possible arrangements, there is clearly a potential role for overarching international oversight. As we have pointed out before (McCombie et al., 2022), there could be major advantages in establishing a widely accepted governance system for an MNR with the IAEA taking on an active oversight role. Such activities are not currently within the Agency’s remit, but the scale and importance of this proposal merits thought being given to making it possible. It might extend to the development of a set of regulatory standards specific to an MNR, with the IAEA acting as an overarching regulator, with the role of an authority rather than an agency. A multinational repository, serving many countries, would be best served by a multinational regulator. There are parallels in terms of the accepted roles of other international authorities, such as the World Trade Organisation (WTO) and International Maritime Organisation (IMO). Bringing together both safety and security/safeguards arrangements and oversight under one agency would be beneficial. Failing that, the IAEA should at least act as an archive of information on all geological disposal facilities (both national DGRs and MNRs), for which common archiving standards would need to be established. Centralising and standardising data records for all geological disposal facilities would mitigate the problems that will arise from inevitable geopolitical changes.

As noted earlier in this article, the number and range of interests and competences of organisations that could be involved in an MNR project necessitates a high degree of openness and transparency in terms of information. With the exception of certain security-sensitive data on nuclear materials, there is everything to be gained with respect to ensuring long-term viability and safety of a geological disposal project by wide dissemination of information. For an MNR, this internationalisation is clearly essential. It should also be so for any national DGR because national boundaries change, even over the course of a few hundred years and the ownership of a DGR site will change with them. Many national boundaries in Europe have changed considerably over the last few hundred years and countries have both come and gone. The proud owners of many jewels of national infrastructure are not the peoples who built them. The Alhambra in Andalusia was built by Moors not Spaniards; the Pont du Gard in Provence was not built by the French, but by Romans; the Temple of Segesta in Sicily not built by Romans or Italians, but by Greeks. A future user of archived information is not necessarily going to be the implementing host country of any DGR. Having information stored centrally, in a common form and available to any user, is thus an essential objective towards which the international community should be working.

3.3 Financial characteristics

It is accepted that the producers of radioactive wastes are responsible for their safe management and disposal—the so-called Polluter Pays Principle. It is therefore necessary to secure financing for construction, operation, closure and monitoring of a DGR and to allocate all of these costs in a fair way to all its users. Because of the long-term nature of geological disposal, it is increasingly the case that funds are accumulated from income generated during the production of the wastes, to be disbursed over the lifetime of the disposal project. The most common way to raise the funds is through a surcharge on the price of nuclear electricity, at least up to the start of repository operation. Thereafter, income at the DGR can be generated based on unit prices for waste emplaced.

In some national DGR programmes, the waste management funds are contributed to by independent nuclear power producers, with mechanisms having been established for fair allocation of the costs involved. Clearly, in a multinational arrangement, these mechanisms can be adapted, taking into account the specific inventories that user countries of an MNR would like to dispose. The ERDO Working Group has suggested a model for allocating costs between MNR participants that covers the spectrum from major NPP countries to those with only a few cubic metres of R&D wastes (ERDO Working Group, 2011). Of course, willingness to share the costs of repository implementation and operation will be contingent on users being in agreement with the cost estimates and having insight into the cost effectiveness of the project. For an MNR, this will again require transparency going beyond normal commercial operations.

A key question is whether funds are established centrally by the waste producers or are centralised and segregated, usually under control of the national government. Similar decisions will have to be made for an MNR, where the options are a single fund in the host country or national funds that transfer monies as required. In either case, there will be strict requirements on transparency and on fund management. The host country will need to be convinced that the users will continue to be able to meet their commitments and the users will have to be convinced that the funds are being effectively invested. This will require technical and commercial information, some of which is often not openly available, to be transparently and accessibly documented. Potential problems, such as countries withdrawing from the MNR arrangement, or failing to meet their financial commitments, are mirrored by parallels in national programmes with diverse repository users.

There are also financial benefits associated with an MNR project. As in many national programmes, the host community and/or region may expect to have economic benefits. In the MNR case, the host government might also expect direct benefits, because there may be a perceived additional burden in accepting foreign wastes. Hosting an MNR must, by definition, be a voluntary process and the benefits expected by all may be higher than in a purely national programme in which expropriation of sites often remains a possibility of last resort. On the other hand, a government hosting a multinational repository could possibly reap financial benefits large enough to have a major effect on its GDP. The economics, financial arrangements and balance sheets of a major MNR project are thus likely to be under the spotlight of international financing mechanisms and organisations, especially if the project is commercially based—again requiring a considerable degree of information transparency.

3.4 Liability characteristics

Apart from the issues concerning future financial liabilities, there are decisions to be taken on allocating responsibilities for agreeing a suitable monitoring regime, potential remediation activities, the content, form and location of data to be archived and future use of the repository site. Once again, although all such decisions are also needed in national DGR programmes, they will be more complex in the case of an MNR. Moreover, the multinational agreements that are established need to be maintained over many decades, even if the political situation or the national energy policies change in any partner countries. Potential conflicts of interest must also be dealt with. For example, the host country may insist on a monitoring programme that is more extensive, long-lasting and expensive than user countries deem to be necessary.

Although a very low probability scenario, responsibility for remediation or even retrieval in the event of problems arising with the operation or closure of the repository, will be a sensitive topic. It seems plausible that user countries may be prepared to share responsibilities for some long time into the future rather than having to accept full responsibility for a national facility. However, the details need to be negotiated in advance, agreed and documented. The archiving issue should not be a major problem since it is generally agreed that national programmes also have a responsibility to ensure that the key data on a closed and sealed repository are available to the global community. As has been pointed out above, the fluidity of national boundaries, certainly on the European continent, has been such that a repository site which needs to be monitored for several hundred years may well assume different nationalities over that period.

As discussed in Section 3.1, various options can be envisaged for the long term ownership and control of the repository site. The host government may hold title to the land from inception and grant rights to the MNR implementer. Alternatively, title may be held by the MNR implementer and revert to the government on closure, or be released for further use and transferred to other owners—but with the host government maintaining records and institutional controls. One option is that the host government cedes ownership of the land to an international organization for the duration of operations. In all cases, however, it seems inevitable that the long-term responsibility for a DGR or MNR must revert to the national government.

A counterposed aspect, introduced earlier in this article, is that long-term *liabilities* seem increasingly likely to have a positive offset—long-term *value* of the disposed materials. Attitudes to managing wastes change, along with technologies. Forty years ago, geological disposal was a required and absolute conclusion for most long-lived wastes, although even then there was ambivalence on how to treat SNF. The divergence persists between national programmes adopting either direct disposal or recycle, and it can be expected that attitudes will continue to adjust as the technologies and economics of advanced fuel cycles become better established. What is regarded as a liability today may become an asset in the future—consider a DGR containing several thousand tonnes of uranium, copper, burnable actinides and rare earths. Deciding if and how to exploit this asset, who should benefit and to what extent, will require considerable thought during the formulation of the financing, ownership and data management rules of an MNR project.

4 Conclusion

From the foregoing discussions, we would highlight the following principal conclusions:

- Geological repositories will be a feature of the underground environment over the next centuries, with MNRs being inevitable.
- Although they are currently often regarded as a liability, DGRs could also become an asset and, for this reason and simply for reasons of informed curiosity, it is quite likely that any DGR will not remain undisturbed for long.
- Propagation of information on geological repositories is essential to ensure that any unintentional disturbance causes no significant harm, and that intentional intrusion can be done safely, but the critical period during which

nations must work together to manage information is arguably only a few hundred years.
- This will not be difficult to achieve: only a limited amount of information is critical, and preservation and communication should not present big issues if properly managed.
- Because of the multigenerational timescales of DGRs (national or multinational), it would be more transparent to both present and future generations if safety requirements, as defined through national regulations, were more consistent and more harmonised. It is confusing for the public to observe that countries have different dose limits, different timescales for analysis, different requirements on retrieval, different levels of waste characterisation etc.
- For an MNR, information requirements are naturally more complex than for a national DGR: for example, regulators from a number of nations may have to be informed and even to approve the repository project, and legal mechanisms to ensure that all users have sufficient assets to cover potential future liabilities may be weaker than in the national case.
- However, implementation of MNRs will enhance the global sharing of competence, experience, knowledge, data, etc. and thus will enhance global safety and security.
- The number of players involved in an MNR mean that the information exchange issues are automatically internationalised, which is a good thing, given the transience of national boundaries: there is a lesson here for national DGRs.
- We should start now on developing an oversight capability (most plausibly at the IAEA) that would sweep together all aspects of safety and security, including safeguards: this should be motivated by development of MNRs, but central archiving of all DGR information at such an agency would be beneficial to mitigate against future geopolitical change.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

Authors NC and CM are contracted by the Secretariat of the ERDO Association.

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