Transport of Carbon Dioxide and Radioactive Waste

Darío R. Gómez and Michael Tyacke

Abstract A comparative assessment of carbon dioxide (CO_2) and radioactive waste transport systems associated with electricity generation was undertaken on the basis of 15 criteria grouped under three areas, namely the transport chain, policy aspects and state of the technology. For CO_2, we considered exclusively the transport that would take place under a future large-scale capture and storage infrastructure. Our study allowed a certain hierarchy of criteria to be identified for the comparative assessment. We discovered that the physical state for transport (fluid for CO_2 and solid for radioactive waste) and the volumes involved are the key properties for determining the most suitable modes of transport. These are pipelines (on- and offshore) for liquid or supercritical CO_2, and rail, ship or truck for spent nuclear fuel and high-level waste. Ship-based transport has also been suggested for future applications of large-scale CO_2 transport. Leakage and accidental releases are the main risks underlying the safety policies of both transport systems. However, because of the large differences between transport chains, safety standards are specific to each system. Regulatory frameworks both at national and international levels are at very different stages of development. Routing is a common concern for both transport systems. In this study we cite over 90 references covering the main literature published on this topic over the last decade.

Keywords Transport • Carbon dioxide • Spent nuclear fuel • High-level waste • State of the technology • Policy aspects • Regulatory framework

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1 Introduction

We aim here to compare the transport of carbon dioxide (CO_2) and that of radioactive waste (RW) from electricity generation through to their respective geological disposal. This may seem a somewhat paradoxical undertaking, considering that no facilities at either end of these transport chains have been built to date.

CO_2-rich streams, for instance, are presently being transported in the oil industry for the purpose of enhanced oil recovery (EOR) and also in a few CO_2 capture and storage (CCS) projects worldwide (DGC 2008; Maldal and Tappel 2004; Statoil 2007). This CO_2 is not captured from thermal power plants but is either of natural origin or captured from industrial facilities such as natural gas processing or chemical plants. However, it is expected that after 2010 new CCS demonstration projects worldwide will involve CO_2 capture from power plants (Gale 2009). Furthermore, our assessment presupposes that a large deployment of CCS will occur in the future at a scale estimated in the range of several hundred to several thousand million tonnes of CO_2 per year worldwide (Gale et al. 2005), with power plants being significant CO_2 sources.

With respect to RW, geological disposal has yet to occur. However, progress towards implementation is evident in a number of countries that have adopted this option as the reference long-term management solution for their high-activity, long-term RW (NEA 2008). Consequently, there is currently no transport of RW to the last step of the chain; however, transportation of spent nuclear fuel (SNF) and high-level waste (HLW) from nuclear power generation and other sources for different purposes has evolved over 4 decades.

This comparative assessment then draws on international experience in the transport of CO_2 and RW, although the existing systems do not yet connect the initial stage (for CO_2) or the final stage (for RW) of the transport chains associated with electricity generation. Within this framework, we have looked at several aspects of three broad areas, namely the transport chain itself, its associated policy aspects and the state of the art of both technologies.

For the transport chain we have considered the requirements and associated technical aspects of the conditioning process that is necessary before actual transportation of the CO_2-rich stream captured from the fossil fuel-fired power plants or the SNF or HLW from the nuclear fuel cycle can take place.

We have characterized the central transport system according to five inherent attributes: (1) the appropriate physical state of the waste for transport; (2) the volumes involved; (3) the means of transport; (4) the experience obtained thus far by industry; and (5) the energy requirements and associated environmental loads, particularly additional greenhouse gas (GHG) emissions. Finally, we have briefly looked at the ways of transferring waste from the transport system to the disposal site. We have also considered the environment, safety and risk, particularly the characterization of the main risks and the availability of statistics on incidents.

Policy issues concerning the status of the international regulatory framework have also been evaluated. The transport of hazardous goods is usually a highly political issue; therefore we have looked at public acceptance issues associated with the transport of CO_2 and RW.

The last step in characterization concerns the state of the art of the technology, the maturity of the science, engineering and regulatory aspects and the gaps in knowledge.

These three broad aspects are presented in the relevant sections below for each transport chain. The chapter concludes with a discussion regarding similarities and differences between all elements selected to characterize the transport systems of CO_2 and RW.

2 The CO_2 Transport Chain

Transport is the step that connects the first and last elements of a CO_2 capture and storage system. Presently, CO_2 transport takes place on- and offshore using several methods, including pipelines, ships, trucks and rail. Recent assessments (Berger et al. 2004; Svensson et al. 2004) have indicated that pipelines (on- and offshore), ships (offshore) and combinations of these are the most cost-effective alternatives for the bulk transport of CO_2 associated with a large-scale CCS infrastructure. The CO_2-rich stream from the capture facilities needs to be conditioned to meet the requirements of the transport alternative chosen. That is why, following Aspelund and Jordal (2007), we consider that the CO_2 transportation chain starts with the gas conditioning of the captured CO_2-rich stream and ends with its injection in a high-density phase (see Fig. 1), although conditioning has previously been considered to be part of the capture system. After gas conditioning, the captured CO_2-rich stream needs to be compressed ahead of the pipeline suction point or liquefied for ship-based transport.

2.1 *Conditioning*

CO_2 is transported to the storage site in liquid (ship-based) or supercritical phase (pipeline) to make the best possible use of the transport capacity. Removal of water and certain impurities is required before the captured and conditioned CO_2-rich gas is ready for transmission.

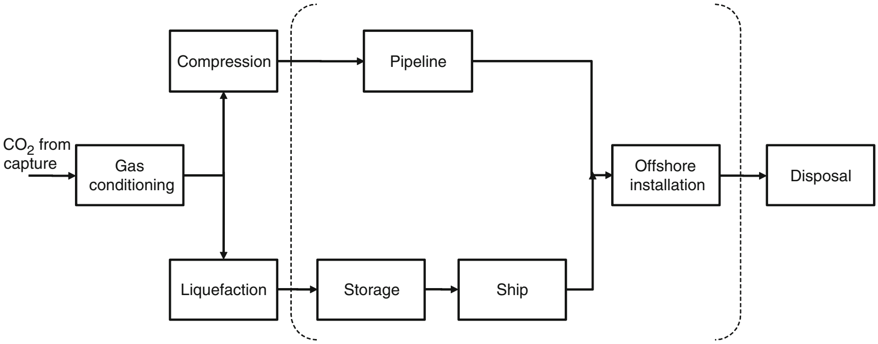


Fig. 1 CO_2 transport chain including conditioning and disposal (Based on Aspelund and Jordal 2007)

Water must be removed to avoid corrosion, freezing and the formation of solid hydrates that can block pipelines, valves or other equipment (Birkestad 2002; Heggum et al. 2005; Aspelund and Jordal 2007; Seiersten and Kongshaug 2005). Depending on the pressure of the captured CO_2-rich gas stream, three or more compression stages are typically required to reach transport conditions. The bulk of water (and other liquids) is removed in each of the compressor suction drums to prevent the ingress of liquid into the compressor. Active dehydration is generally necessary to avoid corrosion and hydrate formation and thus meet the requirements for transport.

Gas conditioning is designed so that the CO_2 stream leaving the capture process satisfies both transport and reservoir specifications. This stream contains a number of impurities in the form of non-condensable gases that differ depending on the CO_2 sources and the type of capture systems. The presence of sulphur compounds, particularly hydrogen sulphide, may raise health and safety concerns. Most of these non-condensable components must be removed for ship-based transport to avoid liquefaction temperatures that may cause the formation of dry ice. This removal is not strictly necessary for pipelines, but it is nevertheless convenient from an economic standpoint. In addition, the presence of small amounts of these non-condensable gases has a major impact on flow properties in terms of influencing the relationship between pipeline pressure drop, on the one hand, and temperature and elevation, on the other (Farris 1983).

For pipeline transport, compression of the captured CO_2 stream is the most power consuming operation of the conditioning step and involves large investment costs. For the ship-based transport chain, the liquefaction system is typically the most energy-intensive process (Aspelund et al. 2006).

Aspelund and Jordal (2007) recently authored a thorough study on the conditioning of CO_2-gas rich streams for CCS. They considered pipeline and ship transport for nine types of streams reported in the benchmark study by Kvamsdal et al. (2007) that assessed different approaches for capturing CO_2 from a reference 400 MW combined cycle plant. The authors reported that the overall energy requirements for the conditioning processes were typically between 90 and 120 kWh/t CO_2. As electricity is required for compression, average GHG emissions would depend on the primary energy supply and on the fuels used for heating purposes.

2.2 *Transport*

After the CO_2 has been conditioned, it is ready to be sent to the pipeline suction or to intermediate storage for subsequent ship loading. This section deals with the transport step itself.

2.2.1 State of Matter for Transport

The operating regions for pipeline transport and the suggested operating conditions for large-scale ship-based transport are depicted in Fig. 2. The thin triangle at the

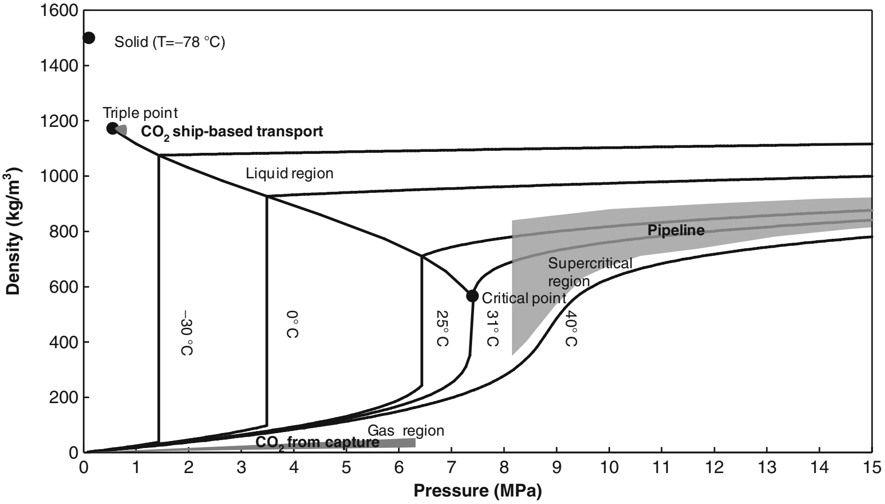


Fig. 2 Key physical CO_2 properties for pipeline and ship-based transport (Based on Aspelund et al. 2006, with data from Lemmon et al. 2005)

bottom of the phase diagram indicates the conditions under which the CO_2-rich stream is delivered from the capture system.

Pipelines operate beyond CO_2 critical pressure (7.38 MPa), mainly in the 8–10 MPa range, in which density versus compression ratio is normally optimal. Higher pressures require more energy and investment costs with little gain in density. However, higher inlet pressures (up to 20 MPa) may be required to overcome the pressure drop along the pipeline without adding intermediate booster stations. The lower pressure limit depends on the CO_2 phase behaviour and is chosen to avoid two phase mixtures. Operating temperatures are in the 4–38°C range. The upper temperature limit is set by the exit conditions of the compression unit and the maximum allowable temperature of the external pipeline coating. The lower temperature limit is determined by the winter soil temperature.

Semi-pressurized vessels at 1.4–2 MPa are presently used to transport liquid CO_2 by ship in much smaller volumes than would be expected for a large-scale implementation of CCS. Conceptual designs for future implementation recommend operating conditions near the triple point (0.52 MPa, 56.6°C) to keep CO_2 in liquid phase close to the lowest-possible pressure to allow large-volume cargo tanks (pressure vessels) to be built with practical wall thickness. In principle, CO_2 could also be transported by ship as a solid. However, Aspelund et al. (2006) have discarded this option on the basis that complex loading and unloading procedures would make it economically unfeasible.

2.2.2 Volume

Gas volumes and concentration levels of CO_2 from thermal power plants depend on the type of fuel used and the excess air level used for optimal combustion conditions. Concentration levels by volume range from 3% to 4% for natural gas-fired power plants up to 14% for coal power plants (Gale et al. 2005). The capture system produces gaseous CO_2-rich streams with typical specific volumes ranging from 300 kg CO_2/MWh for natural gas combined cycles up to more than 800 kg CO_2/MWh in the case of coal power plants (Thambimuthu et al. 2005). It is preferable to capture these CO_2-rich streams from power plants from large point sources (>100,000 t CO_2/year). In 2000, such sources worldwide numbered 4,942 and their associated emissions amounted to 10,539 million tonnes of CO_2 (Mt CO_2).

Presently, several Mt CO_2 per year are transported for EOR and ~2 Mt CO_2 per year for CCS. A large-scale deployment of CCS would require the transportation of several hundreds to thousands million tonnes of CO_2 per year worldwide.

2.2.3 Modes

Pipelines are the preferred option for the land-based transport of large quantities of CO_2 across long distances up to 1,000 km (Skovholt 1993). The pipeline structure depends on the required transport capacity, diameter, inlet pressure, route, need and location of booster pumps, pressure regulators and valves. In mountainous areas, terrain elevation is key, as the static head increases with downhill flows and decreases with uphill flows, which influences the temperature profile in the pipeline. Ideally, the simplest approach is to boost the CO_2 pressure at the suction point to drive the fluid along the whole length of the pipeline as far as the injection point. This is not always possible, and it may be necessary to include intermediate boosters and/or pressure regulators (Farris 1983). Additional considerations include special features for compressors and pumps to compensate for the poor lubricating properties of dry CO_2 and the use of sealing materials (Barrie et al. 2004; Gale and Davison 2004; DGC 2008).

The potential of a large-scale infrastructure to transport several million tonnes of CO_2 per year by ship has received attention in recent years from researchers who have proposed several conceptual designs (Aspelund et al. 2004a, b, 2006; Aspelund and Jordal 2007; Barrio et al. 2004; Berger et al. 2004; Haugen et al. 2009; Hegerland et al. 2004; Ozaki et al. 2004; Svensson et al. 2004).

Aspelund and co-workers (Berger et al. 2004; Barrio et al. 2004; Aspelund et al. 2006) developed a conceptual design for a large-scale ship-based transport of ~2 Mt CO_2 per year in the North Sea. Ozaki et al. (2004) also assessed a system for the transport of ~6 Mt CO_2 across distances in the range of 200–12,000 km. These integrated designs consider all the equipment and machinery necessary to carry out all the steps from conditioning to injection, namely intermediate storage, loading, ship-based transport to the storage site and unloading.

Intermediate storage at harbours would be required for ship transport, as CO_2 is typically captured in a continuous process whereas ships are generally loaded batchwise. At present, steel tanks are used to store CO_2; however, it has been suggested that rock caverns could also be used for this purpose (Svensson et al. 2004).

The loading system from the onshore storage tanks to the ship includes piping between tanks and ship, pumps adapted for high pressure and low temperature CO_2 service, marine loading arm and a return line for any vaporized CO_2 generated at the ship (Aspelund et al. 2006; Barrio et al. 2004; Ozaki et al. 2004). The cargo tanks are first filled and pressurized with gaseous CO_2 to prevent contamination by humid air and the formation of dry ice (Doctor et al. 2005).

When the delivery point is onshore, the liquid CO_2 is unloaded from the ship into temporary storage tanks. For offshore delivery, the use of a submerged turret loading system has been suggested to transfer the CO_2 from the ship to a platform for further injection (Barrio et al. 2004; Aspelund et al. 2006).

2.2.4 Experience

The transport of high purity CO_2 was originally developed to supply CO_2 for injection in EOR. In the USA there are more than 6,000 km of pipelines (US DOT 2008a) that transport several million tonnes of mostly naturally occurring CO_2 annually. Industrially produced CO_2 (e.g. from gas processing, coal gasification, fertilizer and ethylene plants) is transported for use in EOR in a limited number of cases (Gozalpour et al. 2005). The oil industry has more than 37 years' experience in successfully transporting and injecting CO_2 for EOR operations.

For storage purposes only, CO_2 from natural gas processing has been transported onshore in Algeria since 2004 and also in the first long distance (170 km) offshore pipeline of the Snøhvit project at 318 m below sea level in the Norwegian North Sea (Maldal and Tappel 2004; Statoil 2007). In the well known Sleipner gasfield development in Norway there is no need for a long pipeline. Here, after CO_2 has been captured at an offshore platform, its pressure is boosted to 8 MPa and it is then piped to a nearby platform for injection (Hansen et al. 2005). In the Weyburn-Midale project, the CO_2 stream captured from the Dakota Gasification Company's synfuels plant (in North Dakota, USA) is liquefied and transported 320 km by pipeline to the Weyburn field and the Apache's Midale field (both located in Saskatchewan, Canada). This large international collaborative research programme is aimed at exploring and testing key scientific and technological aspects of the long-term storage of CO_2 used in EOR (IEA GHG 2005).

At present, CO_2 is routinely transported by tankers with a capacity of up to ~1,500 t CO_2. The much larger ships needed for a large-scale CO_2 infrastructure can be built based on experience in the construction and operation of semi-pressurized liquefied petroleum gas (LPG) and liquefied natural gas (LNG) ships (Barrio et al. 2004; Ozaki et al. 2004; Aspelund et al. 2006). CO_2 tankers of this type can be constructed in 1–2 years, depending on the ship's size, by the same shipyards currently building LPG and LNG tankers (Doctor et al. 2005).

2.2.5 Energy Requirements and Generation of Waste and/or Greenhouse Gas Emissions

The pipeline transport of the captured CO_2 generates additional emissions, as energy may be needed for intermediate boosters that compensate for pressure drops along the pipeline. The need for these boosters depends on the length of the pipeline, the characteristics of the terrain and the diameter of the pipeline. Boosters may be avoided by increasing the pipeline diameter and reducing the flow velocity. Waste generation is relatively low and disposal is readily available. Greenhouse gases may be emitted from vented streams containing CO_2 and from compressors, depending on the energy supply.

Since a transport system based on large-scale semi-pressurized ships has not been implemented to date, estimates of energy requirements are available only from design studies. Ship fuel consumption of 25 kWh/t CO_2 was reported for a 20,000 m^3 tanker by Aspelund et al. (2006). The demand for unloading is about 7 kWh/t CO_2. GHG emissions are associated with energy requirements, and the levels depend on the assumptions that the modellers have made in their design about the characteristics of the energy supply. The ratio between CO_2 emitted from ships and transported CO_2 is proportional to distance and decreases when larger and lower-speed ships are selected.

2.3 *Disposal*

At this step, the CO_2 that has been transmitted via pipeline or ship is transferred to geological storage via one or more injection wells. The design of the injection system depends on the conditions at the point at which the transported CO_2 is delivered as well as the geometry of the reservoir and its physical characteristics such as faulting, porosity and permeability, which determine the flow rate and pressure required for injection. (This is covered elsewhere and is not further discussed in this chapter.) The main design variables include: (1) number of wells required; (2) well diameter; (3) the need for additional boosters and the corresponding injection pressure; and (4) the maximum injection flow rate (Cockerill 2005).

The injection system is typically composed of a pressurized surge storage tank, injection pumps (if needed), piping to distribute CO_2 to the injection wells, and monitoring and control equipment (Smith et al. 2002). The injection well consists of two or more concentric protective casings, with the injection tube as the innermost part. The main purpose of the exterior casing is to protect aquifers and to prevent water contact with the intermediate protective casing.

For offshore CO_2 storage the injection wellheads can be located on a fixed platform above the waterline or on the seafloor and fitted with valves to control fluid distribution. Regarding the CO_2 injection developments in the North Sea, the former option has been adopted in the Sleipner field (Hansen et al. 2005) and the latter in the Snøhvit field (BERR 2007).

2.4 Environment, Safety and Risks

As CCS is a new technology still under development and few projects have been carried out, many of the legal and regulatory implications are not yet widely understood (Mace et al. 2007). For the same reasons, social research into public perceptions and acceptance of CCS is still at an early stage of development, with only a few finished or ongoing studies (ETP-ZEP 2006). Within this framework, it is often difficult to isolate the specific issues associated with CO_2 transport from the general context concerning regulatory requirements, public acceptance and communication of the entire CCS system. We have made an effort here, however, to discuss specific questions concerning transport; for the general framework the reader is referred to the respective background chapter.

2.4.1 Characterization of Main Risks

Leakage and accidental releases, the main risks associated with CO_2 transport and injection, are typically of a short-term and local nature. They may occur at hazard levels spanning from small leaks to major failures or ruptures of pipes, vessels, pumps or compressors. CO_2 transport safety is often likened to that of natural gas and hazardous liquid transport systems. Unlike other gases or liquids regulated as hazardous materials, pure CO_2 is neither combustible nor toxic. However, because it is heavier than air, compressed CO_2 tends to pool near the ground, displacing all the oxygen, and forming a vapour cloud that can cause respiratory problems including suffocation and even death. The US National Institute for Occupational Safety and Health (NIOSH 1995) has established a value of 40,000 ppm for the immediately dangerous to life or health concentration (IDLH) of CO_2. This is based on statements: (1) by the American Conference of Governmental Industrial Hygienists that a 30 min exposure at 50,000 ppm (5%) CO_2 produces signs of intoxication, and a few minutes of exposure between 70,000 and 100,000 ppm produces unconsciousness; and (2) by the American International Health Alliance that 100,000 ppm is the atmospheric concentration that is immediately life threatening. The consequences of a release may entail further risks if the transported CO_2 contains substantial amounts of hazardous or toxic impurities, particularly hydrogen sulphide (Doctor et al. 2005). (According to NIOSH the exposure threshold at which hydrogen sulphide is immediately dangerous to life or health is 100 ppm.)

Under pipeline conditions a large, sudden release of CO_2 could have catastrophic consequences in a populated area. Therefore pipeline routing must be carefully considered with a view to assuring the rapid dispersion of any leak to prevent CO_2 accumulation, to selecting well ventilated areas and to avoiding depressions such as valleys. Moreover, pipeline blowdowns during maintenance need to be undertaken as quickly as possible (Gale and Davison 2004). Typically, pipeline control and monitoring are performed by means of a supervisory control and data acquisition (SCADA) system. The use of emergency shutdown valves that are activated automatically is common practice to mitigate risks associated with leaks and their propagation.

The transportation of supercritical or liquid CO_2 also involves risks of long-running brittle fractures due to the effects of cooling around leaks and long-running ductile fractures due to phase changes during depressurization. Crack arrestors are normally installed along the pipeline to prevent the propagation of fractures (Race 2006).

Several pipeline risk assessments have been undertaken that consider different design and operating conditions and also several release types (Kruse and Tekiela 1995; Turner et al. 2006). For details and the main results of these risk assessments the interested reader is referred to the original publications.

Collision, foundering, stranding and fire are some of the risks involved in waterborne navigation. For CO_2 tankers, there is risk of asphyxiation if a collision causes the rupture of a tank. One way of improving safety is to adopt the high standards of construction and operation currently applied to LPG tankers. Liquid CO_2 released onto the sea surface in the event of a ship accident could lead to the formation of hydrates, with ice and temperature differences inducing strong currents. Under poor ventilation, a CO_2 cloud may form and present similar respiratory problems to those of onshore releases, possibly causing stoppage of the ship's engines (Doctor et al. 2005). Risk mitigation involves routes being carefully planned and personnel highly qualified.

Care must be taken when designing large-scale CO_2 liquefaction systems and storage tanks, especially in harbour areas, where a gas detector system is required. Procedures for loading and unloading liquid CO_2 near the triple point have been developed to avoid dry ice formation, as blockage and operational problems may occur (Aspelund et al. 2004a). During offshore unloading, the vessel should be kept at a safe distance from the platform (Barrio et al. 2004).

Risks during injection are typically associated with releases like blowouts or leakage due to mechanical failure of the injection equipment (Hendriks et al. 2005). The main reasons for these are inner and outer corrosion of tubing, outer corrosion of casings and wellbore blockage. Measures normally taken to prevent outer corrosion consist of lining the exterior of the tube with polyethylene and filling the annulus between the protective casing and tubing with a corrosion inhibitor fluid (Vendrig et al. 2003). To avoid wellbore blockage, it is essential to ensure that CO_2 stays in supercritical phase to minimize hydrate and ice formation.

In the event of leakage through the wellbore annulus, CO_2 can migrate into adjacent reservoir zones and aquifers, with the risk of contaminating underground sources of drinking water. Checks for wellbore integrity are normally undertaken by the operator to protect aquifers and prevent reservoir cross-flow. All materials used in the injection well should be designed to anticipate peak volume, pressure and temperature (Cailly et al. 2005).

2.4.2 Statistics of Incidents

Statistics on pipeline incidents are available from the US Department of Transportation (US DOT 2008b), which requires the reporting of accidents and incidents involving CO_2 and other hazardous liquid pipelines. Within these data, of the 3,695 serious accidents reported on hazardous liquid pipelines since 1994, only 36 involved CO_2 pipelines. Among the 36 incidents, only one injury, and no fatalities, were reported. It is difficult to statistically characterize the reasons for the incidents because they are so relatively few in number. Based on previous statistics, Gale and Davison (2004) have indicated that while most incidents in CO_2 pipelines were related to the pipeline itself (failures of relief valves, failures of weld/gasket/valve packing and corrosion), the principal cause of incidents for natural gas pipelines was external force, such as damage by excavator buckets. This contrast should be taken into account when estimating failure frequencies for CO_2 pipelines from the available failure databases of natural gas or hazardous liquid transmission in the context of risk assessment.

2.5 Regulatory Requirements

Development of national standards is under way in several countries, in which CO_2 transport is not specifically addressed, and where the adaptation of existing environmental rules governing drilling, injection and gas transportation is typically the favoured approach. Transport of CO_2 across national boundaries and transport by ships and via sub-sea pipelines is covered by various international legal conventions. The following features of the transport system play a role in determining the applicability and application of regulatory and liability regimes: (1) mode (pipeline, ship or a combination of both); (2) geographical location (within or across national boundaries, onshore, offshore, proximity to population centres); (3) land ownership (private, publicly owned or managed); (4) impacts (local or transboundary); (5) risks (to the public, to the terrestrial, marine or aquatic environment, to groundwater); and (6) identity of the party responsible for damages resulting from accidental release of CO_2 (pipeline owner or supervisor, ship owner).

These characteristics also influence the design of permission procedures, the identity of the relevant permit authority or authorities, responsibility for monitoring, and environmental impact assessment procedures (Hendriks et al. 2005). Existing international liability regimes may need to be extended or clarified to cover the bulk transport of CO_2 in view of the large scale envisaged for these activities and the corresponding risk levels.

The design and operation of pipelines is typically governed by national codes and standards. Our discussion focuses mainly on the regulatory status in the USA, which is the country with the most extensive pipeline network and the largest construction and operating experience. The USA currently has three different regulatory schemes for transportation of energy resources by pipeline (FERC 2008). Under the scheme governing CO_2 transport to date, pipelines are sited under state law and there is no federal role involved. Operators of interstate pipelines are free to set their own rates and terms of service. Safety standards and reporting requirements for CO_2 pipelines are aimed at ensuring safety in pipeline design, construction, testing, operation and maintenance, corrosion control and qualification of personnel. Similar regulations are in place in Canada.

The transport and injection of CO_2 in sub-seabed repositories may involve different categories of marine pollution under the relevant international conventions, namely the UN Convention on the Law of the Sea (UNCLOS), the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, the London Protocol and the International Convention for the Prevention of Pollution from Ships (MARPOL). The categorization depends on whether the captured CO_2 is transported by ship and injected from platforms, transported and injected from land-based pipelines running across or beneath the seabed, or injected from facilities used for offshore oil and gas exploration and exploitation (Hendriks et al. 2005). Regional rules include the conventions and protocols of the United Nations Environment Programme (UNEP) Regional Seas Programme and other regional and subregional arrangements. The MARPOL Convention includes regulation of emissions from routine operations and accidental pollution associated with ships, fixed and floating platforms and mobile offshore drilling rigs that might be used to inject CO_2 into the seafloor. Annex III of the Convention, dealing with the prevention of pollution by harmful substances in packaged form and implemented through the International Maritime Dangerous Goods (IMDG) Code, is relevant for the bulk transport of liquid CO_2 for injection. Ships transporting liquefied CO_2 would be subject to the general requirements under Annex III, which lists detailed standards on packing, marking, labelling, documentation, stowage, quantity limitations, exceptions and notifications for preventing pollution by harmful substances (Hendriks et al. 2005).

2.6 Public Acceptance

Most of the available studies addressing the acceptance of CCS technology focus on its role as a GHG mitigation option and on the issues concerning CO_2 disposal (de Coninck and Huijts 2004; Gough et al. 2002; Itaoka et al. 2004; Palmgren et al. 2004; Shackley et al. 2005; Wright et al. 2007; ETP-ZEP 2006), although few of them have considered issues related to CO_2 transport (Itaoka et al. 2004; Wright et al. 2007). In general terms and with the exception of the results of Palmgren et al. (2004), these studies seem to indicate that, if given adequate information about the climate change context, the public may look favourably on CCS.

The study by Itaoka et al. (2004) detected four important factors influencing public opinion: (1) environmental impacts and risks, including the possibility of leakage; (2) the effectiveness of CCS as a GHG mitigation option; (3) societal responsibility for CO_2 mitigation; and (4) concern that CCS would allow continuation of the current levels of fossil fuel use. Concern about accidents during CO_2 transport was one of the 19 items making up the first of these factors.

Wright et al. (2007) provided a prioritized assessment of perceptions and issues affecting the deployment of CCS. It considered seven regions/countries (North America, Europe, Australia and New Zealand, Japan, China, India and South Africa) and five stakeholder groups in each region (government, industry, non-governmental organizations, the public, and research and development organizations).

Of the 27 issues included in the survey, two were specific to transport and concerned routing and safety of CO_2 pipelines. Routing was considered as a potentially negative driver of public opinion in 71% of answers and safety in 65%.

2.7 *State of the Technology*

2.7.1 Science and Engineering

The onshore transport of high purity CO_2 by pipeline is a mature technology with more than 6,000 km of pipeline worldwide and an annual capacity of several million tonnes. Most of these pipelines presently transport naturally occurring CO_2 and, to a minor extent, CO_2 extracted from natural gas processing or other industrial applications. The streams that, in the future, will originate in facilities capturing CO_2 from combustion processes will contain different types of impurities. In their recent review paper on CCS, Steeneveldt et al. (2006) have indicated that there is a need to improve understanding of the influence of such impurities on the thermophysical properties of these CO_2-rich streams and how possibly changing properties will affect the design and operating conditions of the pipeline transport system.

The information necessary to undertake environmental and health impact assessments of onshore pipeline transport is relatively well defined and does not involve significantly different requirements to those of the many impact assessments conducted every year. However, there is still a need for a comprehensive definition of exposure limits and for a deeper discussion about modelling the release, as well as about the preferred models available for CO_2 dispersion (IEA GHG 2007; Turner et al. 2006; Koornneef et al. 2009).

Leakage from offshore pipelines and wells could adversely affect large areas through CO_2 dissolution in the surrounding seawater and subsequent acidification thereof, which could detrimentally affect marine ecosystems (Chadwick et al. 2007). This reinforces the need to ensure that the risk of leakage is minimized through proper site selection, design and monitoring. Owing to gaps in knowledge regarding the effects of ocean acidification on marine ecology, these effects remain uncertain as this area of science is relatively young (IEA GHG 2007). There is also uncertainty about the impact on the onshore water environment. The 318 m pipeline of the Snøhvit project in the Norwegian North Sea is the only offshore facility that has been built to date. The learning curve concerning offshore pipeline operation and maintenance has thus only just started.

There is experience in transporting relatively small quantities of CO_2 by ship. However, large-scale ship-based transport of CO_2 has yet to occur, and only conceptual designs for this option are available. These designs rely on the experience in the construction and operation of semi-pressurized LPG and LNG tankers. It remains to be assessed if there are rock caverns close to harbours that would be suitable for the intermediate storage of hundreds of thousands of cubic metres of CO_2 in a similar manner as is done for LPG.

2.7.2 Regulatory Aspects

The regulatory framework for CO_2 transport is under way in most countries interested in the deployment of large-scale CCS. For pipeline transport an evolutionary approach based on existing environmental rules governing drilling, injection and gas transportation is the preferred option. There are presently no recognized specifications for CO_2 quality in terms of its transport for CCS purposes; however, it is likely that future specifications for the transport of CO_2 will take into consideration maximum allowable impurity content in the storage site, the local legislation governing CO_2 transportation, and the type and level of impurities that are acceptable.

Several authors (Gale and Davison 2004; Hendriks et al. 2005) consider that the substantial experience regarding the regulation of CO_2 pipelines in North America could be used by other countries as a reference. However, some key actors in the USA believe that there may be still gaps in the existing rules addressing the construction and operation of CO_2 pipeline networks required for a large-scale deployment of CCS. Furthermore, Kerr et al. (2009) have recently indicated the concern of the UK regarding uncertainties associated with CO_2 transport; the country has called for initiatives and projects to develop best practice guidelines for onshore and submarine CO_2 pipelines.

The United States Environmental Protection Agency is currently working on the regulation of CO_2 injection to ensure that this activity will not endanger underground sources of drinking water. Key components of the proposed regulation include requirements related to: geological site characterization to ensure that wells are sited in suitable areas to limit the potential for migration of injected and formation fluids into an underground source of drinking water; well construction and well operation to ensure that the wells are properly constructed and managed; well integrity testing and monitoring to ensure that the wells perform as designed; and well closure, post-closure care and financial responsibility to ensure proper plugging and abandonment of the injection wells (US EPA 2008).

No integrated international framework is yet available for ship-based transport, offshore pipelines and injection of CO_2 in sub-seabed repositories, which may involve different categories of marine pollution under the relevant international conventions.

2.7.3 Policy Aspects

Further assessment is necessary to evaluate public perception of CO_2 transport. Most of the studies available are of a general nature and only a few of them deal with specific issues of transport. It is likely that acceptance of transport in general may become more problematic since this is the most visible part of the CCS system (Coleman 2009).

There are considerable gaps in the knowledge of the effects of CO_2 release and impurities on the marine environment, both on specific organisms and on ecosystems. There is a certain amount of knowledge about the effects of CO_2 on animals and vegetation in the terrestrial environment; however, effects on smaller organisms are less well researched. Human health effects are well understood, but effects on members of the population with suboptimal health are less well understood.

2.7.4 Cost Estimates

Transport costs depend strongly on the distance and the quantity transported. Pipeline material costs are a function of the diameter and the thickness of the pipeline, the linear weight and the price of the selected steel, and the price of the external coating. The type of pipeline (onshore or offshore) and the characteristics of the route and the terrain play an important role in determining the final investment and operating and maintenance costs.

Offshore pipelines that typically operate at higher pressures and lower temperatures than onshore pipelines are generally more expensive. Doctor et al. (2005) have compiled cost estimates for both onshore and offshore pipelines that have been reported in several studies. These studies have considered the pipeline only and did not include either conditioning or compression costs. Investment costs for onshore pipelines, expressed in terms of the diameter and the length of the pipeline, were US$0.6–1/m/km for pipeline diameters in the 0.1–1.2 m range, with lower values corresponding to larger diameters. For offshore pipelines, investment costs were US$1–2/m/km for the same range of pipeline diameters. Doctor et al. (2005) also reported transport costs per mass of CO_2 for a nominal distance of 250 km as a function of both pipeline diameter and mass flow rate of CO_2. The costs decrease exponentially with either of the two variables. For a pipeline diameter of 0.3 m, transport costs related to the use of onshore pipelines are in the US$2.5–4.2/t CO_2 range and in the US$4.2–5.5/t CO_2 range for offshore pipelines. For a pipeline diameter of 1 m, costs in the US$0.7–1.4/t CO_2 range include both types of pipeline.

The cost of ship-based transport depends mainly on the ship size and the transport distance. Table 1 provides an overall picture of the results from the studies by Ozaki et al. (2004) and Aspelund et al. (2006), the main features of which were

Table 1 Summary of key parameters for the cost estimation of ship-based transport of CO_2

	Ozaki et al. (2004)	Aspelund et al. (2006)
Annual amount of CO_2 transported (Mt)	6	2–4
Distance from storage tank to unloading (km)[a]	200–12,000[b]	[c]
Ship capacity (kt CO_2)	10, 30, 50	22
Liquefaction requirements (kWh/t CO_2)	130	110
Oil consumption by ship (kWh/t CO_2)	n.a.	25
CO_2 emissions/CO_2 transported (%)[d]	12–30	1.4
Cost (US$/t CO_2) for the range of distances considered	17–58	20–30
Cost (US$/t CO_2) for a distance of 1,000 km (Ozaki et al. 2004) and 750 km (Aspelund et al. 2006)	20	25

[a] Distances correspond to one-way trips from intermediate storage to injection; costs are for the round trip journey

[b] The results of this study reflect the very wide range of selected transport distances

[c] Distances limited to the North Sea

[d] The difference in the results may be explained in part by the assumptions made by Aspelund et al. (2006) that the required power in their model has no associated CO_2 penalties since it comes from a power plant with 100% CO_2 capture while the corresponding penalty in the model by Ozaki et al. (2004) is ~10%

summarized in Sect. 2.2.3. Care is necessary when comparing the pipeline costs reported above that do not include conditioning costs with those reported in Table 1 that include the liquefaction facility, which is an important component of the investment and, particularly, the operating costs. Other cost elements are associated with storage tanks, loading and unloading facilities, the sailing route and harbour fees. For distances under 1,000 km the estimated costs in both studies are in agreement, in the US$20–25/t CO_2 range. Aspelund et al. (2006) reported the following contributions to the cost components considered in their assessment: liquefaction (42%) > ship (30%) > unloading (16%) > storage (9%) > loading (3%).

3 The Radioactive Waste Transport Chain

The life cycle transport chain for nuclear material used to generate electricity starts at the point of the raw uranium's removal from a mine and ends with the final disposal of the spent nuclear fuel (SNF) or high-level waste (HLW) in a deep geological repository. This study is limited to radioactive waste (RW) associated with nuclear reactor fuel and does not discuss the transport of raw uranium or other types of nuclear materials, such as sealed sources, medical isotopes and low-level waste.

The nuclear fuel transport begins at the fuel fabrication facility. After fabrication, the nuclear fuel is transported to a nuclear reactor site where it is placed in the reactor and burned to generate heat to make electricity. When the nuclear material in the fuel has been used up or spent, the spent fuel is removed from the reactor and placed in a storage pool for several years to allow it to cool. From the storage pool, the SNF can be transported in one of three directions. It can be sent to a dry storage facility, to a reprocessing facility, or directly to disposal (see Fig. 3). If, however, the spent fuel is reprocessed, there are two other transport considerations. These are: (1) transport of the fuel material retrieved from the spent fuel reprocessing back to fuel fabrication for use as new fuel; and (2) transport of the treated HLW (i.e. vitrified/solidified waste) to either an HLW storage facility or directly to disposal.

3.1 Conditioning

There are two types of RW that need to be conditioned for transport: SNF and HLW, both of which form in the nuclear reactor and which are segregated and recovered from the SNF reprocessing. Conditioning of the SNF is primarily done by placing the material into transport packages, also known as transport casks. Conditioning of the HLW requires the liquid radioactive material from the reprocessing process to be solidified, usually by vitrification, before being placed into the transport packages. The outer transport casks are generally intended for multiple and extended use possibly for more than 20 years.

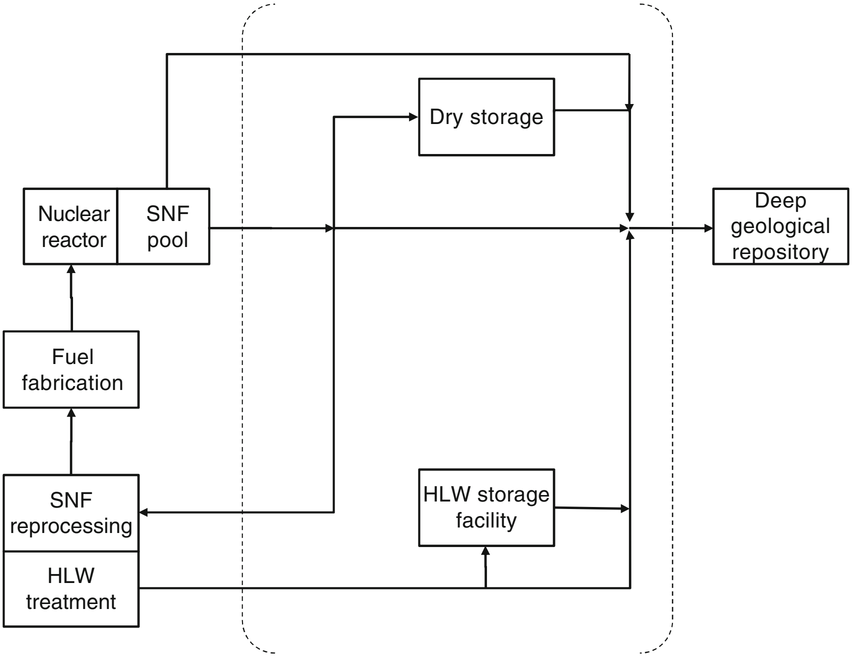


Fig. 3 Example of the nuclear fuel/material/waste transport chain

The reusable nuclear material retrieved from reprocessing requires minimal conditioning prior to transport to the fuel fabrication facility. In most cases this material is in powder form and is placed in special canisters. This material has minimal radioactivity and does not require the same rigorous transportation packaging as is needed for RW. However, this material involves extensive security requirements for transport because of its purity, its convenient handling and the ease with which it can be used for proliferation purposes.

Nuclear fuel is usually composed of fingernail-sized pellets of uranium dioxide inside hollow metal rods, typically constructed of zirconium oxide alloy (zircaloy). These fuel rods are generally between 3.5 and 4.5 m in length and are bundled together into fuel assemblies, each weighing between around 275 and 685 kg (National Research Council 2006). The assemblies are placed in commercial nuclear reactors and used to generate heat through a nuclear reaction, i.e. nuclear fission. It takes 1–2 years for the assemblies to lose their ability to produce heat or become spent; hence the term ‘spent nuclear fuel’. As part of the process of expending energy during a nuclear reaction, the fuel becomes highly radioactive and thermally hot. Spent fuel emits radiation as a result of radioactive decay. The SNF is removed from the reactor and placed in specially designed storage pools near the reactors where it is cooled in preparation for transport to dry storage, reprocessing or final disposition.

Conditioning of SNF for transport from the reactor storage pool to dry storage, reprocessing facility or deep geological repository is quite an involved process. The highly radioactive nature of the material means that it must be handled with great care and with scrupulous regard for the safety of the workers, the public and the environment. The SNF must be conditioned to protect against criticality, radiation exposure and radioactive contamination under normal and hypothetical accident conditions. The first protective barrier is the cladding around the fuel meat in the fuel assemblies. The second and most important protective barrier is a specially designed, tested and licensed performance-based package. Transport packages provide protection in terms of containment, shielding, heat management and nuclear criticality safety for the radioactive material that they contain (National Research Council 2006).

Containment is provided by cladding around the nuclear fuel and/or by placing the nuclear material in canisters that are custom-designed for SNF. Specially designed transport packaging for shipment provides the final and main layer of containment.

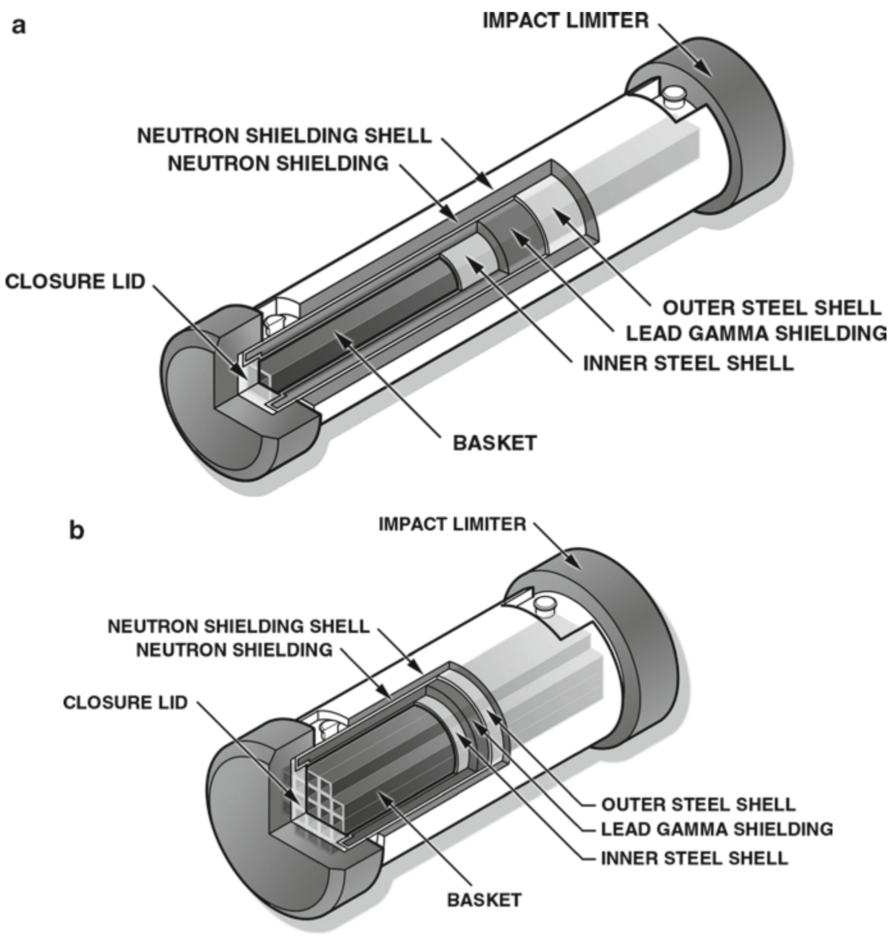
To shield the workers, the public and the environment from the hazards of radiation, the package is enclosed in multiple layers of dense material that limit the amount of radiation that can escape from it. The structure of an SNF transport package most commonly consists of an inner and an outer stainless steel structure which enclose the materials that shield against gamma radiation; in some designs, the structure is comprised of a monolithic thick-walled steel cylinder which at the same time provides gamma shielding. Neutron shielding is usually placed over the outer cylinder enclosing the gamma shielding materials and held in place by a thin-walled stainless steel structure (EPRI 2004). Typically, for every tonne of SNF there are approximately 4 t of shielding materials in the package.

It is of utmost importance to ensure that internal nuclear reactions (i.e. self-sustaining nuclear reactions such as those that occur in the reactor) do not take place and cause criticality events while the RW is being transported. Criticality control is achieved by limiting the amount of RW in the package, minimizing nuclear moderator, and/or ensuring adequate spacing of the materials within the package. Thus, inside the package is a structure (referred to as a basket) that provides support, positioning, criticality safety and heat management.

The package is closed with one or two steel lids, which have an airtight seal to the package body. The package is also designed with impact limiters to absorb mechanical forces generated in the event of transport accidents and to provide thermal protection for the lid seals in case of fires (National Research Council 2006).

In most cases the transport of SNF and HLW is done in so-called Type B packages (see Fig. 4). These packages come in over 150 types and are built to maintain gamma and neutron radiation shielding, even under extreme conditions (WNA 2008).

The energy requirements for SNF conditioning is limited to what is needed for the nuclear material handling facility–primarily electricity for lights, cooling and heating. Conditioning of HLW requires the use of high-temperature furnaces capable of vitrifying matrices for a wide spectrum of fission products and specific elements such as sodium, phosphate, iron, molybdenum or actinides. The furnaces operate at temperatures of between 1,150°C and 1,600°C (Petitjean et al. 2002).



(a) Generic truck cask.

Typical specifications are:
Gross weight (including fuel): 25 t
Cask diameter: 1.2 m
Overall diameter (including impact limiters): 1.8 m
Overall length (including impact limiters): 6 m
Capacity: Up to four pressurized water reactor (PWR) or nine boiling water reactor (BWR) fuel assemblies.

(b) Generic rail cask.

Typical specifications are:
Gross weight (including fuel): 125 t cask diameter: 2.4 m
Overall diameter (including impact limiters): 3.4 m
Overall length (including impact limiters): 7.6 m
Capacity: Up to 26 PWR or 61 BWR fuel assemblies.

Fig. 4 Schematic representation of typical spent fuel transportation casks (Source: United States Nuclear Regulatory Commission website http://www.nrc.gov)

The waste generated during SNF conditioning consists of small quantities of low-level RW generated during the loading and unloading operations. High-level liquid waste is also generated during SNF reprocessing. The amount of GHG emissions depends on the energy sources supplying the facility, particularly the fuel used to generate the heat for the furnace.

3.2 Transport

Once the RWs have been conditioned and loaded into the appropriate transport package, they are ready for transport. This section looks at the main characteristics associated with the transport itself.

3.2.1 State of Matter for Transport

The RWs are in a solid form when transported. As previously described, nuclear fuel is originally solid and remains in that state after it has been spent. HLW is solidified through a glass-forming process that reduces its volume and eliminates the gaseous fission products that it contains (National Research Council 2006).

3.2.2 Volume

Nuclear power produces an amount of spent fuel of roughly the same mass and volume as the fuel that is fed to the reactor. This amounts to 2.7–3.6 g/MWh (Ewing 2006; Garwin 2008; EIA 2008).

SNF transport casks designed for road transport weigh normally about 25 t, however, some casks may weigh up to 40 t, not only necessitating the use of heavy trucks but also potentially requiring the consideration of routing particulars and special permits (EPRI 2004). Packages designed for railway transportation and/or intermodal barge shipping weigh up to 125 t. There is roughly a six to one fuel capacity advantage of rail casks over road casks.

Presently, the largest inventories of HLW and SNF from both defence and power production are stored in the USA and Russia. The SNF inventory of the USA was about 42,000 t in 2000 and that of Russia about 8,500 t in 1999. The worldwide SNF inventory is expected to grow significantly over the next 30 years at least. For example, the USA inventory will nearly double to about 83,800 t by 2035. Data reported to the International Atomic Energy Agency (IAEA) by 23 countries (excluding the USA and Russia) indicated that, overall, inventories of SNF through 1996 had accumulated to 42,466 t and are projected to be 90,472 t by 2014 (National Research Council 2001).

3.2.3 Modes

There are three modes of transporting SNF or HLW (i.e. road/truck, railway and ship/barge). Transport by road/truck and rail is the most likely mode for overland transport. The difference in capacity between one large rail cask that can accommodate roughly six times more SNF than a truck cask makes rail a more efficient transport mode. Both road and rail transport require specialized equipment. Road transport uses specially designed trailers that provide integral tie downs to fasten the cask to the conveyance, while a 125 t rail cask requires more than a four-axle goods wagon to transport it (EPRI 2004).

Ship/barge transport is typically used for shipments between most continents, island countries, and in situations where sea transport is easier than transport through transit countries.

3.2.4 Experience

The international community has decades of experience in the conditioning, regulating and safe handling of SNF and HLW. Some industrialized countries have considerable experience, while other less developed countries or countries without nuclear reactors have little or none. There are no complete statistics on the worldwide transport of RW. Based on a literature search and a series of informal contacts with about 25 of its member states, the IAEA was able to compile information on shipments of SNF to 2000 (National Research Council 2006). A summary of this information, as presented by Pope et al. (2001) and modified by the National Research Council (2006), is presented in Table 2. The compilers recognized the informal and incomplete nature of this information as some of the countries contacted did not respond and some respondents provided incomplete or inconsistent data.

In spite of the preliminary nature of this information, it is clear that rail has been the prevalent transportation mode and that, in general terms, the most intensive traffic has occurred within and across the borders of 11 European countries (Czech Republic, Finland, France, Germany, Hungary, Italy, Russian Federation, Slovakia, Sweden, Ukraine and the UK). The disaggregated data compiled by Pope et al. (2001) have also shown that most of the shipments are concentrated in France and the UK and that most of them are destined for the reprocessing facilities at La Hague and Sellafield, respectively. The survey also reported that SNF rail shipments within the UK are made using dedicated trains (i.e. trains carrying only one commodity from origin to destination), whereas shipments to France are made using both scheduled and dedicated trains. These trains share the rails with other freight and pass through large cities. Most of the other spent fuel shipments within or between countries are bound for interim storage (National Research Council 2006).

The sea-based transport system in Sweden, operative since 1985, uses a dedicated ship (M/S Sigyn); heavy trucks are used for complementary land transport at terminals. Dybeck (2004) has reported that up to 2004 some 1,400 transport casks

Table 2 Estimates of spent nuclear fuel shipments worldwide (Source: Pope et al. 2001; National Research Council 2006)

	Europe		Japan		North America	
Mode	Mass of SNF (tHM)	Number of packages	Mass of SNF (tHM)	Number of packages	Mass of SNF (tHM)	Number of packages
Road	81	52				
Road and rail	258	131			2,270	3,020
Mostly rail	45,702–65,142	17,565–34,065				
Sea	4,400					
Sea and land			7,821	2,130		
Unspecified	5,297–5,438	1,507–1,572			100	187
Total	55,738–75,319	19,255–5,820	7,821	2,130	2,370	3,207

Europe: Domestic or international shipments made in or between 11 European countries
Japan: Domestic shipments and international shipments from Japan to France or the UK
North America: Canada and the USA
SNF spent nuclear fuel, *tHM* tonnes of heavy metal (usually uranium)

with SNF and 130 casks with core components had been transported from Swedish reactors to the central interim SNF storage site in Sweden; these shipments amounted to 4,200 t of heavy metal, which is consistent with the information reported by Pope et al. (2001).

3.2.5 Energy Requirements: Generation of Waste and/or Greenhouse Gas Emissions

Standard fuels (mostly diesel oil and fuel oil) and/or electricity are used to supply the power needed to transport the RW. There is nearly no waste generated during the transport of RW. The only GHG emissions are from transport exhaust.

3.3 Disposal

Typically, the SNF or HLW will either be in a specially designed disposal canister when it arrives at the disposal facility, or it will be unloaded and placed into a disposal canister. The canisters will then be transported into the disposal facility using specially designed transport equipment (i.e. special fork lifts, air pallets, transfer casks, etc.).

3.4 Environment, Safety and Risks

Package safety is primarily based on robust mechanical design, the application of a substantial engineering safety margin and the use of protective features to mitigate any physical impacts that may occur during transportation (EPRI 2004).

3.4.1 Characterization of Main Risks

Risks for transporting RW arise from conventional vehicular accidents and exposure to ionizing radiation under both normal and accident conditions. Radiation risks are primarily a concern for transportation workers and for people who live near shipment routes and also for those travelling on these routes (National Research Council 2006).

Packages are effective in shielding well over 99% of the radiation emitted by the SNF or HLW. However, a small amount of radiation, primarily gamma rays, can escape from the interior of the packages and provide external doses to workers and the public (National Research Council 2006). The IAEA (2004) recently summarized the findings of several assessments of dose and risk associated with the transport of radioactive material in the nuclear fuel cycle, indicating that annual individual doses to the public are low (well below 0.1 mSv (millisievert)) and also that annual individual doses to workers are generally low (less than 1 mSv). (The sievert is a unit of equivalent dose (1 J/kg) that considers the type and effect of the radiation). Equivalent dose equals absorbed dose times Q, a quality factor (e.g. $Q=1$ for X-rays and $Q=20$ for alpha particles). These figures are below regulatory limits and also lower than the total annual global per capita effective dose due to natural radiation sources (cosmic rays, terrestrial gamma rays, inhalation and ingestion), which has been reported to be 2.4 mSv (UNSCEAR 2008).

The greatest risk arises from accidents affecting the transportation package, the likely result of which would be damage to the vehicle and/or little to no damage to the package and the RW contained in it. Degradation and/or loss of package containment have the potential to increase such radiation exposure incidents and possibly result in the release of radioactive material from the package to the environment (National Research Council 2006). However, the robust design of transportation packages makes such releases unlikely. Experience thus far indicates that no event of this type has occurred after thousands of shipments and 50 years of RW transport.

Rhoads et al. (1986) have provided a framework for the comparative assessment of the risks associated with a number of activities, including the transportation of hazardous materials such as SNF, explosives, chlorine and propane, as well as natural and man-made phenomena such as lightning, tornadoes, dam failures and industrial accidents. The results of this study showed that the individual risk (i.e. the probability of an individual at risk of dying from this cause in a given year) from SNF transport was 1 in 10^{15}. This risk was 4×10^{7} times lower than for chlorine transport, 7×10^{7} times lower than for propane transport, 4×10^{9} times lower than for railway accidents and 3×10^{11} times lower than for motor vehicle accidents.

Most regulatory bodies have relied on the operational experience of the safe transport of SNF as validation for their regulations. Since the early 1970s, some regulatory agencies such as the US Nuclear Regulatory Commission have undertaken several risk assessments, analytical studies and cask testing programmes to ensure that the regulations governing radioactive materials transport are strong enough to protect the public. EPRI (2004) has recently summarized some significant studies undertaken in the USA concerning: (1) SNF shipping response to severe road and railway accident conditions (US NRC 1987); (2) re-examination of SNF risk estimates (US NRC 2000); (3) additional assessment of SNF responses under actual road and railway transportation accidents unrelated to SNF transport (US DOE 2003); and (4) physical testing programmes of SNF shipping casks (Jefferson and Yoshimura 1978; Huerta 1981; US NRC 2003). These recent assessments have concluded that: (1) the earlier risk assessments were conservative and that the risks associated with SNF transport remain small; and (2) the probability of an accident severe enough to violate the integrity of a SNF cask was extremely small. Consequently, the risk to the general public of any credible accident is also extremely small.

3.4.2 Statistics of Incidents

Notification of accidents and incidents in transport is typically required by the regulations of most countries where competent authorities are responsible for receiving and recording these events. Individual countries keep track of accidents and incidents involving radioactive materials within their borders (Shaw et al. 2001; McClure 1997; EPRI 2004).

The IAEA maintains a database (Events in the Transport of Radioactive Material (EVTRAM)) of such information (Young 2004). However, this database has been supported only to a limited extent by IAEA member states, which report on a voluntary basis, and the experience thus far has shown that this type of reporting system leads to incomplete information (Shaw et al. 2001).

The combined information from national and IAEA data sources indicates that in spite of transportation accidents involving SNF casks in several countries, there have been no serious injuries to transport workers, emergency response personnel, or the general public from the radioactive contents of the casks (EPRI 2004).

3.5 Regulatory Requirements

The transportation of SNF is perhaps the most comprehensively regulated of all hazardous materials (EPRI 2004). The international recommended requirements for the packaging and transport of radioactive material have evolved over 4 decades, resulting in today's IAEA regulations for the safe transport of radioactive material (IAEA 2005; Pope 2004). This set of regulations includes requirements for shippers and carriers; packaging, including analysis or testing for both normal and accident conditions of transport; security and physical protection; training and emergency response; and inspection and quality assurance (EPRI 2004). In addition, each nation has developed its own requirements following, in the vast majority of cases, the IAEA advisory regulations. Adherence to these regulations ensures that the transport package: (1) is appropriate for the radioactive material to be transported; (2) is designed according to a quality assured process; (3) is properly prepared for transport; (4) is properly labelled in accordance with national and international requirements; (5) is properly operated, handled and maintained in accordance with the requirements stated in the transport package safety case; (6) has the appropriate documentation during transport to provide the necessary information to those involved in transport and those responding to any incident that may occur; and (7) performs in a predictable manner under normal transport and accident conditions.

The IAEA advisory regulations for the safe transport of radioactive materials were first published in 1961 (IAEA 1961). They are reviewed on a biennial basis and are revised as needed; this periodic review is essential to ensure safety. The IAEA regulations are now recognized throughout the world as the uniform basis for both national and international transport requirements and have been adopted by over 60 countries, the International Civil Aviation Organization (ICAO) for air transport, the International Maritime Organization (IMO) for sea transport, and regional transport organizations (Pope 2004). In addition, all of the IAEA regulatory requirements have been incorporated into the latest edition of the United Nations recommendations on the transport of dangerous goods (UN/SCETDG 2001).

The IAEA regulations for the safe transport of radioactive materials (IAEA 2005) contain requirements for both normal conditions of transport and hypothetical accident conditions. For the particular case of SNF and HLW transport,

Table 3 Tests specified by IAEA regulations for demonstrating the ability of a package to withstand normal and accident conditions of transport (Based on IAEA 2005, Section VII)

Test	Brief description
Normal conditions of transport	
Water spray	The specimen is exposed to a spray simulating an exposure to rainfall of approximately 5 cm/h for at least 1 h
Free drop	The specimen is dropped from specified heights according to the package mass, from 0.3 m (>15 t) to 1.2 m (<5 t)
Stacking	Unless the shape of the packaging effectively prevents stacking, the specimen is subjected to a compressive load of: 5 × (actual package mass) or 13 kPa × (vertically projected area of the package), whichever is greater, for a period of 24 h
Penetration	A 6 kg bar of 3.2 cm diameter with a hemispherical end is dropped from a height of 1 m and is directed to fall, with its longitudinal axis vertical, onto the centre of the weakest part of the specimen
Accident conditions of transport	
Free drop	The specimen is dropped from a height of 9 m onto a flat, essentially unyielding horizontal surface, so as to suffer maximum damage
Puncture	The specimen used in the free drop test is dropped so as to suffer maximum damage from a height of 1 m onto a solid mild steel bar of circular section (15 cm in diameter and 20 cm long), which has been rigidly mounted perpendicularly on an unyielding horizontal surface. The steel bar has a flat and horizontal upper end with its edge rounded off to a radius of not more than 6 mm
Thermal	The specimen used in the previous mechanical tests is fully engulfed in a hydrocarbon fuel/air fire for 30 min in sufficiently quiescent ambient conditions to assure a minimum average flame emissivity coefficient of 0.9 and an average temperature of at least 800°C. The specimen is subsequently exposed to an ambient temperature of 38°C, subject to specified solar insolation conditions and subject to the design maximum rate of internal heat generation within the package by the radioactive contents for a sufficient period to ensure that temperatures in the specimen are everywhere decreasing and/or are approaching initial steady state conditions
Water immersion	A separate undamaged specimen is immersed under a head of water of at least 15 m for a period of not less than 8 h in a position that will lead to maximum damage. In addition, for packages designed to contain more than $10^5 A_2$, an enhanced water immersion test is specified under which the specimen is immersed under a head of water of at least 200 m for a period of not less than 1 h

the requirements specify that Type B packages should be designed to withstand severe accident conditions without a loss of containment or an increase in external radiation to levels that would endanger emergency responders or the general public. Under normal transport conditions, the regulations require that if Type B packages are subjected to the water spray, free drop, puncture and stacking tests briefly described in Table 3, the corresponding specimens must maintain their containment effectiveness by restricting the loss of radioactive contents to not more than $10^{-6}A_2$/h. (A_2 is the activity value of radioactive material which is given in special tables in IAEA (2005) and is used to determine the activity limits for the requirements of these regulations.) Under accident conditions of transport, the IAEA regulations specify that if Type B packages were subjected to the mechanical, thermal and immersion tests presented in Table 3, they should:

(i) Retain sufficient shielding to ensure that the radiation level at 1 m from the surface of the package would not exceed 10 mSv/h with the maximum radioactive contents which the package is designed to contain; and
(ii) Restrict the accumulated loss of radioactive contents in a period of one week to not more than $10A_2$ for krypton-85 and not more than A_2 for all other radionuclides.

3.6 Public Acceptance

Establishing a route for a nuclear material shipment can be very political and highly emotional if the public is made aware of the shipment. Some countries (i.e. the USA and Germany) require that the public be made aware of certain nuclear material shipments, whereas other countries (i.e. the Czech Republic, Russian Federation, Slovakia and Ukraine) specifically prohibit dissemination of information to the public for security reasons. The countries that notify the public of nuclear shipments provide a significant amount of public/media awareness training and outreach before the first shipment is made. There is a significant amount of experience of effective outreach of this nature.

Although the security of radioactive materials in transport, understood as ‘the protection of humankind and the environment from the potential consequence of malicious, purposeful and unlawful acts of an individual or group’ (Pope and Luna 2004), is not new for the nuclear transport industry, it has received increased attention following recent world events. To meet the security needs, the IAEA began in 2002 a series of activities to provide additional guidance on the basis of model regulations developed by the United Nations Sub-Committee of Experts on the Transport of Dangerous Goods (UN/SCETDG 2001). The implementing guide on security in the transport of radioactive material (IAEA 2008) constitutes the main result of these activities. In addition to considering the quantity of the radioactive material being transported, the transport modes and the type of packages being used, the guidance requires measures: ‘to deter, detect and delay unauthorized access to the radioactive material’, ‘to identify the actual possible malicious acts involving any consignment', and 'to provide rapid response to any… malicious acts involving radioactive material while in transport or storage incidental to such transport.' The guidance specifies that establishing 'an adequate security regime for the transport of radioactive material is the responsibility of each State', and discusses the role of the operators in implementing adequate security measures.

3.7 State of the Technology

3.7.1 Science and Engineering

The science and engineering for making RW shipments is well established. The engineering for the packages is fully recognized and the science for ensuring the shielding, criticality, containment, and structural integrity is well known. An important aspect of assuring safety is the graded approach to package design, whereby a proportionate robustness of packaging is required according to the materials being carried and the safety risk of individual components. There is over 50 years of experience in this area and it continues to improve as technologies and experience evolve.

Type B packages are performance-based packages; their design, licensing and fabrication require complex expertise in technical design areas such as structural engineering, heat transfer, nuclear criticality safety and radiation shielding. As discussed in Sect. 3.5, regulatory requirements impose a set of strict performance criteria on designers and manufacturers to ensure that each Type B package can withstand normal transportation and hypothetical accident conditions.

The analytical tools used for the design of any SNF transportation cask and its other transportation system components (structural and thermal computer codes, nuclear codes for criticality safety and shielding) are utilized well within their demonstrated range of benchmarked capability. Physical testing may be conducted during design in several circumstances such as when new materials are used, in cases in which numerical methods may not be fully capable of accurately predicting behaviour or where performance data are incomplete. Full-scale testing of components or partial-scale testing of components and packages is done using standardized material testing methods (EPRI 2004).

The construction of SNF and HLW packages normally follows the industrial practices used in the fabrication of large pressure vessels. Specialty materials such as lead, depleted uranium or hydrogen-containing materials are uniquely identified and specifically tested to assure compliance with the design specifications. Before its initial use, each completed cask undergoes acceptance testing that includes leak checking, hydraulic testing for integrity, shielding continuity testing and thermal testing. During the entire life of the cask, it is operated and maintained to specified requirements and under a strict quality assurance programme with approved procedures. In general terms, no other hazardous material container undergoes the same level of scrutiny (EPRI 2004).

3.7.2 Regulatory Aspects

No sector of transport is regulated more stringently than the nuclear transport industry, which has to take many actions regarding: (1) requirements for loading, stowage, carriage, handling and unloading of the package; (2) restrictions on the mode of transport and routing instructions; and (3) emergency and safety arrangements (IAEA 2005). However, the underlying philosophy, based on a set of performance criteria for packages rather than specific design specifications, requires that the package provide the primary means of ensuring the necessary safety during incident-free transport and during accidents, whatever mode of transport is used (Green 2004).

The nuclear transport industry (Green 2004) and other stakeholders (IAEA 2004) have called for greater standardization, harmonization, global application and simplification of transport safety standards. Among harmonization issues, the industry has mentioned: (1) different time schedules for introduction of new regulations in different jurisdictions; (2) different interpretation of the regulations by different competent authorities (e.g. the order in which package tests are carried out); and (3) different assumptions being used by different authorities in carrying out reviews of the criticality safety of packages. These harmonization issues may lead to considerable time intervals between the renewal of a package certificate in one country and the relevant revalidation in another country, occasioning delays in transport. One key question in the implementation concerns the independent reviews of package designs and revalidation of approved packaging carried out by various national competent authorities in the context of international shipments. As sometimes different underlying assumptions are used, a single design may require, for instance, the preparation of multiple criticality analyses to obtain base approval and foreign validation (Green 2004).

Transport security has received increasing attention, and the IAEA has recently published an implementing guide for security in the transport of radioactive material (IAEA 2008). International transport security standards have also been developed, especially by IMO. In some cases, international standards are supplemented by national requirements. However, there is a need for harmonization because differing requirements between national jurisdictions may lead to greater complexity, with the potential for confusion and misinterpretation (Green 2007). In addition, the transport industry still faces the challenge of balancing the traditional safety approach, which needs to be clearly declared, with the need to maintain security (Morgan-Warren 2003).

3.7.3 Policy Aspects

Transport of RW is very political and, although its low associated risk has been estimated based on sound science and demonstrated over 50 years of experience, the nuclear transport industry still needs to make efforts to win over the public. However, there is extensive experience showing that well planned and executed public and media training and outreach programmes, demonstrating that shipments can and will be carried out safely and securely, serves to overcome the general public's fears, resulting in minimal opposition. Although a significant amount of knowledge is required to do this effectively, issues such as denials that shipments contain nuclear waste, delays to shipments, and transport security, remain major challenges (Green 2007).

3.7.4 Cost Estimates

Costs depend on factors such as the volume of waste shipped, the origin and destination of shipments and the specific route used. However, costs for truck and rail shipments can be estimated based primarily on the weight of the load and the length of the trip (Tang and Saling 1990). Other components of the cost may involve leasing and demurrage costs, the latter being the waiting time for the cargo to be loaded or unloaded at the originating and terminating facilities.

Many studies like the recent one by the University of Chicago (2004) have adopted a reference value of US$63/kg of uranium (2003 prices) for the transportation costs of SNF. This value was selected from the report by NEA (1994), which addresses relatively short transportation distances within the European area, assuming, for sensitivity reasons, transport costs in the range US$25–100/kg of uranium.

4 Comparative Assessment of the Transport of CO_2 and Radioactive Waste Associated with Electricity Generation

All the criteria composing the three guiding principles that we proposed for this comparative assessment, namely transport chain, policy aspects and state of the technology, are summarized and addressed in Table 4, while the main findings are discussed hereafter.

4.1 Transport Chain

For large-scale operations associated with CCS, CO_2 is transported in liquid or supercritical state to make the best possible use of the transport capacity. This is totally different for SNF, which remains in the same solid state as the original

Table 4 Comparison between the transport of CO_2 and radioactive waste resulting from the generation of electricity

CO_2	RW
Transport chain	
1. Conditioning	
1.1. Type of processing up to the inlet of the transport system	
Removal of water and certain impurities. Compression before pipeline suction. Liquefaction for ship-based transport	Proper packaging for the type of material and the mode of transport
1.2. Energy requirements. Generation of waste and/or greenhouse gas emissions	
Compression and liquefaction are very energy intensive. Waste generation is relatively low. GHGs depend on the energy supply	Standard energy requirements. Small quantities of low-level radioactive waste may be generated during loading and unloading
2. Transport	
2.1. State of matter	
Supercritical or liquid for pipeline. Liquid for ship-based transport	Solid for both SNF and HLW
2.2. Volume	
~300 kg CO_2/MWh for natural gas-fired power plants 600–800 kg CO_2/MWh for coal power plants	3–4 g SNF/MWh. Typically, for every tonne of SNF there are ~4 t of protective shielding materials in the reusable package
2.3. Modes	
Pipeline (on- and offshore), ship and combinations of these are regarded as the most cost-effective alternatives for a large-scale CCS infrastructure	Rail, the dominant mode, is followed by ship for long distances involving maritime transport. Road/truck is the third mode. Air transport is unlikely
2.4. Experience	
Onshore pipeline: >6,000 km pipeline annually transporting several Mt CO_2 Offshore pipeline: The first long distance (170 km, ~2,500 t CO_2/day) pipeline has been constructed in the Norwegian North Sea Ship: tankers with capacities <1,500 t CO_2. Large-scale ship-based transport (2–6 Mt CO_2/year): only conceptual designs are available	Until 2000, 66,000–85,000 tHM, usually uranium of SNF have been transported worldwide in ~12,000 transportation casks Modes in terms of tHM transported: mostly rail (46,000–65,000) > unspecified (~5,000) > sea and land (~12,000) > road and rail (~2,500) > road (<100)
2.5. Energy requirements. Generation of waste and/or greenhouse gas emissions	
Pipeline: Intermediate boosters may be required to compensate for pressure drop along the pipeline *Ship*: Fuel consumption (~30 kWh/tCO_2, for a 20,000 m^3 tanker) > unloading (<10 kWh/t CO_2)	Standard type energy sources are used to generate the power needed to transport the nuclear material (i.e. gasoline and diesel)
Fuel combustion: GHG emissions are associated with pumping through the pipeline or with ship-based operations. *Fugitive*: CO_2 from venting. Waste generation is relatively low and disposal is readily available	There is nearly no waste generated during transport. The only GHG emissions are from the exhaust of the mode of transport

(continued)

Table 4 (continued)

CO_2	RW
3. Disposition (manner of transfer from the transport system to the disposal site)	
Injection system: pressurized surge storage tank, injection pumps (if needed), piping to distribute CO_2 to the injection wells, monitoring and control equipment	Typically, the SNF or HLW will either be in a specially designed canister for disposal when it arrives at the disposal facility or it will be unloaded and placed into a disposal canister
4. Environment, safety and risks	
4.1. Characterization of main risks	
Leakage and accidental releases are the main risks associated with CO_2 transport and injection. They are typically of short-term and local nature *Onshore pipeline*: CO_2 from leaks could accumulate near the ground *Offshore pipeline*: Leaks could adversely affect a large area because of the dissolution and acidification of the surrounding seawater *Ship*: Collision, foundering, stranding and fire are the risks involved *Injection*: Releases or leakage due to mechanical failure of the injection equipment. CO_2 could migrate into adjacent reservoir zones and aquifers	Risks arise from conventional vehicular accidents and exposures to ionizing radiation under both normal and accident conditions Radiation risks are primarily a concern for transportation workers and for people who live near shipment routes and also for those travelling on these routes
4.2. Statistics of incidents	
Data from 36 CO_2 pipeline incidents that occurred in the USA show that most incidents were related to the pipeline itself. These features are different from natural gas pipelines, for which the principal cause of incidents was outside force, such as damage by excavator buckets	Combined data from national sources and the IAEA indicate that while there have been transportation accidents involving SNF casks in several countries, there have been no serious injuries to transport workers, emergency response personnel, or the general public due to the radioactive contents of the casks
Policy aspects	
5. Regulatory requirements	
Development of national standards is under way in several countries. The transport of CO_2 across national boundaries and transport by ships and by sub-sea pipelines is covered by various international legal conventions. The applicability and application of regulatory and liability regimes depend on: transport mode, geographical location, land ownership, impacts, risks and identity of the party responsible for damage	In 1961 the IAEA started publishing advisory regulations for the safe transport of radioactive materials. Those regulations are now recognized throughout the world as the uniform basis for both national and international transport safety requirements. These regulations have been adopted by over 60 countries, the International Civil Aviation Organization (ICAO), the International Maritime Organization (IMO), and regional transport organizations

(continued)

Table 4 (continued)

CO$_2$	RW
6. Public acceptance	
It is difficult to isolate the specific issues associated with CO$_2$ transport from the general context of public acceptance and communication of the entire CCS system. For a large-scale deployment of CCS, public concerns about CO$_2$ transport may be a significant barrier. Public and media awareness training and outreach programmes will be required	There is a significant amount of experience in undertaking public and media awareness training and outreach programmes to demonstrate that the shipment(s) can and will be done safely and securely. Establishing a route for a nuclear material shipment can be very political and highly emotional if the public is made aware of the shipment
State of the technology	
7.1. Science and engineering	
Onshore pipeline: The transport of high purity CO$_2$ by pipeline is a mature technology *Offshore pipeline*: The 318 m pipeline of the Snøhvit project is the only facility that has been built. The learning curve has just started *Ship-based*: There is experience in transporting relatively small quantities of CO$_2$ by ship. Large-scale ship-based transport of CO$_2$ has yet to occur and only conceptual designs for this option are available	The science and engineering for making nuclear material shipments is well established. Type B packages are performance-based packages. The engineering for the packages is fully recognized and the science for ensuring that the shielding, criticality, containment, and structural integrity is well known. An important aspect of assuring safety is the graded approach to package design. There are over 50 years of experience in this area, and it continues to improve as technologies and experiences evolve
7.2. Regulatory aspects	
An integrated international framework is not yet available. The regulatory framework for CO$_2$ transport is under way in most countries interested in the deployment of large-scale CCS	No sector of transport is regulated more stringently than the nuclear transport industry. There has been a call for greater standardization, harmonization, global application and simplification of transport safety standards
7.3. Policy aspects	
Further assessment is necessary to evaluate public perception of CO$_2$ transport	Although low risk has been estimated based on sound science and demonstrated over 50 years of experience, the nuclear transport industry still needs to make efforts to convince people that nuclear transportation is safe

CCS carbon capture and storage, *GHG* greenhouse gas, *HLW* high-level waste, *SNF* spent nuclear fuel, *tHM* tonnes of heavy metal

nuclear fuel, or for HLW, which is solidified before transport. Therefore, the transport of CO$_2$ and nuclear waste essentially differ in the many aspects associated with the transportation of bulk fluids versus the transport of properly identified packages containing solid materials.

For each MWh of electricity, about 300 kg CO$_2$ can be captured from natural gas-fired thermal power plants and 600–800 kg of CO$_2$ from coal-fired power plants. These figures are five orders of magnitude higher than the amount of waste generated by nuclear power plants, which is 3–4 g SNF/MWh. This large difference in specific emissions/waste is reflected in the projected volumes that would be required for a large deployment of CCS, which are estimated to be several hundreds to thousands million tonnes of CO_2 per year worldwide (Gale et al. 2005), while the inventory of SNF worldwide would be several hundred thousand tonnes in 2030, which would definitely not all be transported in 1 year.

The physical state for transport and the volumes involved largely determine the preferred means of transport. They are pipelines (on- and offshore) for liquid or supercritical CO_2 and railways, ship or truck for SNF and HLW. Ship-based transport has also been suggested for future large-scale CCS. Ship-based transport is the only common mode for both transport systems. However, there is a difference between the state of the art for ship-based transport of CO_2 and that of RW. There is a mature market for SNF and HLW, particularly in countries such as Sweden and Japan, while large-scale transport of CO_2 (2–6 Mt CO_2) is at the research phase, with only conceptual designs available.

Conditioning is necessary for the stream of captured CO_2 and the SNF or HLW before they are actually transported. Because of the physical state and the associated risks, the type of processing for each type of material is very different. Removal of water and certain impurities, compression before pipeline suction or liquefaction for ship-based transport are required for CO_2-rich gas. This conditioning is primarily aimed at providing adequate physical properties for transport, with safety playing a secondary role in defining the characteristics of the process. Conditioning of the SNF is primarily done by placing the material into transport packages (denominated Type B packages) while the HLW is subject to a solidifying process (usually vitrification) before being placed in the transport packages. Safety is the main concern for this processing and the specially designed, tested and licensed performance-based transport packages constitute the most important barrier providing protection regarding containment, shielding, heat management and nuclear criticality safety for the radioactive material that they contain.

In spite of the differences between both transport systems, onshore pipeline transport of CO_2 has a somewhat similar level of experience to SNF and HLW transport. The transport of high purity CO_2 was originally developed to supply CO_2 for injection in EOR, and the oil industry has presently over 4 decades of experience in successfully transporting and injecting CO_2 for this purpose. In the USA more than 6,000 km of pipelines annually transport several million tonnes of mainly naturally occurring CO_2. With respect to RW transport, the international community has about 5 decades of experience in the conditioning, regulating and safe handling of SNF and HLW. By 2000, total shipments worldwide had totalled 55,000–75,000 t of heavy metal in 19,000–36,000 packages. Rail was the predominant shipping mode, followed by sea and land.

The transport systems also differ in the infrastructure they require. Pipelines (on- and offshore) must be built especially for CO_2 transport. On the other hand, trucks and trains normally share roads and rails with other vehicles without requiring the construction of a dedicated infrastructure. Maritime shipments of SNF or HLW are usually done in dedicated ships as will be the case for large-scale ship-based CO_2 transport.

In general terms, waste generation is relatively low and disposal is readily available for all the steps of both transport systems. GHG emissions would depend on the structure of the electricity supply and on the transport distance for those modes that use fossil fuels, particularly trucks and ships.

The main risks associated with both transport systems are similar in that they constitute leakage and accidental releases, typically of short-term and local nature. The main difference is the nature and impacts of these releases. Pure CO_2 is neither combustible nor toxic, unlike other gases or liquids regulated as hazardous materials. The main risk of compressed CO_2 is that, being denser than air, it tends to pool near the ground, displacing all oxygen and forming a vapour cloud that can cause respiratory problems, including suffocation and even death. The main risk associated with a damaged SNF or HLW transport package is that of an accidental release resulting in radiation exposure, contamination and/or criticality.

As a consequence of the differences in risk discussed above, the safety measures for both systems also differ. The performance-based approach for Type B packages requires that the package be the primary safety barrier during normal transport and during accidents, whatever mode of transport is used. This is the main difference not only to the transport of CO_2 but also to the transport of many hazardous cargoes where the mode of transport is the only primary safety measure.

The pipeline transport of CO_2 and the transport of SNF and HLW have a similar record regarding incidents. While there have been accidents in both transport systems, there have been no serious injuries to transport workers, emergency response personnel or the general public as a result of the radioactive contents of the packages or CO_2-rich releases.

4.2 Policy Aspects

Of all hazardous materials transport, that of SNF and HLW is perhaps the most comprehensively regulated. The IAEA regulations for the safe transport of radioactive material have evolved over 4 decades and are recognized worldwide as the uniform basis for both national and international safety standards. They include requirements for shippers and carriers; packaging, including analysis or testing for both normal and accident conditions of transport; security and physical protection; training and emergency response; and inspection and quality assurance. This status is quite different from that of CO_2 transport, which is lacking a uniform international approach. Development of national standards is at different stages in several countries ranging from an advanced regulatory scheme in the USA, which is the country with the most extensive pipeline network and the largest construction and operating experience, to countries whose legislation has not yet specifically addressed CO_2 transport. Transport of CO_2 across national boundaries and transport by ships and by sub-sea pipelines is covered by various international legal conventions.

Public acceptance of nuclear material shipments, particularly concerning aspects such as routing and hearings, can be very political and highly emotional.

The nuclear transport industry has extensive experience in providing public and media awareness training and outreach programmes on the safety and security of SNF and HLW transport. We have been unable to register any major problems with respect to the public acceptance of pipeline transport of CO_2 for EOR. This may be because these pipelines are not generally built across very populated areas. However, under a scenario of large deployment of CCS, public acceptance of CO_2 could also encounter problems similar to those involved in RW transport because CO_2 may need to be transported in large amounts over significant distances in populated areas. In that case, the number of people potentially exposed to risks of the CO_2 transport system may be larger than the number exposed to potential risks of capture and storage facilities, and public concerns about CO_2 transport may be a significant barrier.

4.3 State of the Technology

The science and engineering involved in SNF and HLW shipments and CO_2 pipeline transport are well established. Onshore pipeline and all modes of nuclear material shipments are mature technologies. The status is different for CO_2 transport via offshore pipeline or large-scale ships. The learning curve for offshore pipeline transport of CO_2 has recently started with the construction of a 318 km pipeline in the North Sea. Large-scale ship-based transport of CO_2 has yet to occur, and only conceptual designs for this option are available.

There is room for improvement in the regulatory framework of both transport systems. However, while the nuclear transport industry has called for greater standardization, harmonization, global application and simplification of transport safety standards, the CO_2 transport industry still lacks an integrated international approach. The regulatory framework for CO_2 transport is under way in most countries interested in the deployment of large-scale CCS. For pipeline transport an evolutionary approach based on existing environmental rules governing drilling, injection and gas transportation is the preferred option. Ship-based transport, offshore pipelines and injection of CO_2 in sub-seabed repositories may involve different categories of marine pollution under the relevant international conventions.

Further assessment is necessary to evaluate public perception of CO_2 transport. Most of the available studies addressing CCS as a GHG mitigation option are of a general nature, and only few of them deal with specific issues of transport. It is likely that acceptance of transport in general may become more problematic as this is the most visible part of the CCS system. Transport of RW is very political and, although its low associated risk has been estimated based on sound science and demonstrated over 50 years of experience, the nuclear transport industry still needs to make efforts to convince people that it is safe. Issuing denials that a shipment is carrying RW and delays to shipments, together with other problems involving transport security, remain major challenges. Transport security has received increasing attention; balancing the traditional safety approach that requires declaration with the need to maintain security poses a significant challenge.

5 Conclusions

Our discussion of the individual transport systems and the overall picture presented in Sect. 4 allows a hierarchy of criteria for the comparative assessment of the transport of CO_2 and RW associated with electricity generation to be identified. We found that the main factors determining the mode of transport to be used are the volumes involved, the physical state in which the substance will be transported and the radioactive nature of the SNF and HLW. These properties, which are listed below, show that there are more differences than similarities between the systems analysed.

- Volume: rather than being a specific property of each transport chain, the amount that needs to be transported is an inherent characteristic of each electricity generation system (i.e. 300–800 kg CO_2/MWh, depending on the fossil fuel used, versus ~0.004 kg SNF/MWh) and determines the scale of the transport system.
- Physical state: the CO_2 present in the flue gases from any thermal power plant remains gaseous after being captured and is subsequently transformed to a denser phase (liquid or supercritical) to make transport economically feasible; on the other hand, solid nuclear fuel remains in the same state after being spent, while HLW is solidified through vitrification.
- Waste radioactivity: international standards establish specific requirements for performance-based packages that provide the necessary protection for workers and the general public under normal and accident conditions.

The contrast between the most convenient systems, i.e. bulk transport of liquid CO_2 via (mainly buried) pipeline versus surface transport by rail, ship or truck of properly identified performance-based packages for solid RW singles out the main difference. Under a scenario of large-scale deployment of capture and disposal of CO_2, ship-based transport has been pointed out as a future option. In this case, the right ships for this purpose would be much closer to the tankers used for transporting LPG and LNG than to the specialist vessels carrying nuclear cargoes.

There is a similarity in that for both transport systems: (1) leakage and accidental releases are in general the main risks; and (2) the available records of incidents show that there have been no serious injuries as a consequence of any accident. But once again, the distinctive nature of these risks associated with the differences in both chains does not permit a strict comparison. Accordingly, safety standards are specific to each transport system; with the performance-based approach for Type B packages being a unique feature of the nuclear transport industry. There is a need for more exhaustive information of incidents and an effort on the part of both transport industries in this regard would be welcome because: (1) for onshore pipelines, the available specific information comes mainly from the USA and extrapolations from natural gas pipelines do not seem advisable; and (2) for RW transport, the valuable international information from the IAEA's EVTRAM database is somewhat limited on account of the voluntary basis of reporting by member states.

In spite of all the differences, both transport systems share a well established status with regard to the science and engineering aspects of the existing techno logies. Both onshore CO_2 pipelines and RW transport are mature markets and, although the learning curve has recently started for offshore CO_2 pipelines, while large-scale ship-based CO_2 transport is at a research phase, the specialists suggest that fully developed technologies and good experience of natural gas transfer by offshore pipeline or ships would be readily available when needed on a large scale.

There are also differences regarding the two main policy aspects analysed. Regulatory frameworks both at national and international levels are at very different stages of development. For CO_2 transport, some authors have considered more intensive international cooperation in this field as vital (van Alphen et al. 2009). The process followed by the IAEA in developing the regulations for the safe transport of RW may be of interest in the development of a unified international regulatory approach for the safe transport of CO_2. However, pipeline deployment in the oil and gas industries has made it necessary to contemplate a number of site-specific issues, suggesting that strict standardization such as that of RW transport may be unsuitable.

While routing is a common concern for both transport chains, RW transport has had a higher degree of visibility, particularly in countries requiring that the public be made aware of the shipment, than onshore CO_2 transport via buried pipelines, which to date have mainly occurred in areas of low population. A large deployment of CCS may make this transport more visible, and it is difficult to evaluate from the available studies how public opinion would evolve regarding CO_2 transport for disposal purposes. Public concern may focus on the risk of leakages and accidental releases irrespective of the view of CCS as a technology aimed at decarbonizing the power and industrial sectors. In any case, CO_2 transporters may learn from the experience of the nuclear transport industry in planning and executing public and media training and outreach programmes.

When we started planning this comparative assessment, we feared that a study of this kind would be like comparing apples and oranges. We then realized that our aim was to compare the transport rather than the fruits themselves; assuming that the transport of apples and oranges was comparable, we therefore decided to undertake the study. Furthermore, recent research showed that the fruits themselves were not only comparable but quite similar (Barone 2000). As for apples and oranges, the transport systems for CO_2 and RW turned out to be amenable to comparative analysis; however, similarity was not the determining feature. The distinctive nature of CO_2 and SNF or HLW largely determines the numerous differences between the two transport systems.

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