Risk Management of Carbon Capture and Storage: Overview and Future Steps

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Abstract

Carbon capture and storage (CCS) is the attempt to prevent large quantities of carbon dioxide from escaping into the atmosphere and contributing to the greenhouse effect. The paper opens with an introduction to what is involved in capturing carbon dioxide both from natural and industrial sources, processing it, and then injecting it deep beneath land or oceans where it will remain sequestered for a very long time. Public policy, regulatory, and public acceptance issues related to CCS are reviewed briefly. The next sections of this paper first offer a sketch of how risk management is undertaken, using what is known as an "integrated risk management framework" to explain its unique, step-by-step approach. Then two prominent, long-running and quite different Canadian cases in which a risk-based approach has been worked out in some detail – long-term storage of nuclear waste (used nuclear fuel) and prion diseases (especially so-called "mad-cow disease") – are presented. The purpose of this case-comparison exercise is to provide some real-world dimensions to the otherwise abstract discussion of risk management, and to anticipate some of the ways in which the risk management approach to carbon capture and storage is likely to unfold. The paper concludes with some comments on the nature of the risk assessments, and the risk management framework, that will be required in order to build public confidence in the demonstration stage of carbon capture and storage.

1. Introduction and Overview.

According to the International Energy Agency, carbon capture and storage [CCS] "in power generation, industry and fuel transformation could account for 20% of CO_2 savings (6.5 Gt of CO_2 captured and stored annually in 2050)," making it one of the most important strategies in any greenhouse-gas emissions stabilization scenario.[1] CCS includes three separate processes and their associated technologies:

(1) CO_2 capture: Isolating the carbon dioxide gas that is naturally present in fossil fuels (coal, oil, natural gas), as well as the gas produced in industrial waste streams, such as at ethylene plants, and compressing it into a liquid state;

(2) CO_2 transport: Moving the liquified CO_2 from its point of origin to a suitable site for long-term storage, either on land or beneath the ocean;

(3) CO_2 sequestration: Injecting the liquified CO_2 into a suitable geological medium that is likely to hold it in place, deep underground, for thousands of years.

The longest-running project utilizing these processes is the one in Norway, at the Sleipner West gas field operated by Statoil in the North Sea.[2] Since 1996, one million tonnes (1 Mt) of CO_2 annually have been injected into a sandstone formation aquifer at a depth of 1000 metres beneath the ocean floor.

Other current operations include the Salah field in Algeria, run by British Petroleum and its partners, which has been sequestering 1 Mt/year of CO_2 annually beneath the Sahara Desert, and the world's first CCS coal plant near Spremburg, Germany (a relatively small facility).[3] There are also complete demonstration projects such as Australia's Otway Basin facility, where

[1] *Near-term Opportunities for Carbon Dioxide Capture and Storage* (Paris: OECD/IEA, 2007), p. 3. The Wikipedia entry (http://en.wikipedia.org/wiki/Carbon_capture_and_storage) provides a good introduction to the subject.

[2] http://www.statoil.com/statoilcom/SVG00990.NSF?OpenDatabase&artid=01A5A730136900A3412569B90069E947

[3] http://www.bp.com/sectiongenericarticle.do?categoryId=9025049&contentId=7046578 and http://www.sindark.com/2008/09/22/spremberg-clean-coal-plant/

methane and CO_2 are separated, then the CO_2 is liquified and transported through a pipeline to a well drilled into a depleted natural gas field, where 100,000 tonnes per year are being injected some 2 km underground.[4] Finally, in addition to simply storing compressed CO_2 underground, a process known as EOR (enhanced oil recovery) first uses the gas to increase the amount of oil that may be pumped out of a field when it is close to being depleted. Canada's Weyburn-Midale Project in Saskatchewan, the largest CO_2 sequestration facility so far, takes 1.5 Mt of compressed CO_2 annually, which is shipped through a 300-km pipeline from a coal gasification plant in North Dakota, for use in EOR (resulting in a 50% increase in oil recovered), and which is then to be sequestered permanently underground.[5] There is also a natural gas facility in Fort Nelson, British Columbia that presently captures both CO_2 and hydrogen sulphide (H_2S). In 2008 a feasibility project for a storage phase was announced, involving the drilling of test wells into a saline aquifer; if successful, the facility will sequester 1 Mt/year of carbon dioxide.[6]

There are many challenges still to be overcome before CCS can fulfill its potential for being a major contributor to GHG emissions reductions.[7] At the moment there is general agreement that cost represents a formidable obstacle to commercial-scale development: When CO_2 does not have an economic value, as it does when it is used in enhanced oil recovery, all activities associated with CCS will represent an additional cost of production. For the earlier phases of development, incremental costs in Canada are estimated to be in the range of \$40-\$140 per tonne of CO_2 abated, although costs will fall later. (A recent McKinsey & Company

[4] http://www.co2captureandstorage.info/project_specific.php?project_id=160

[5] http://www.ptrc.ca/weyburn_overview.php and http://www.gov.sk.ca/news?newsId=d88b80b2-458d-49e2-9033-a2d5d5295ee7

[6] http://www.scandoil.com/moxie-bm2/carbon/technology_carbon/spectra-energy-to-pursue-feasibility-of-large-scal.shtml

[7] The challenges are presented effectively in the article, "Trouble in store," *The Economist*, 5 March 2009: http://www.economist.com/displayStory.cfm?story_id=13226661&fsrc=nwlgafree.

report looked at the period beginning in 2020, when the early full commercial-scale CCS projects are expected in Europe, and estimated the costs per tonne of CO_2 abated at €35-50, totalling €30 for capture, €5 for transport, and €10 for storage.[8]) Another way of representing these costs, for an energy-production facility such as a coal-fired electricity plant, is to calculate the expected increase in the costs and price of energy when CCS is added. Again, estimates vary widely at this early stage of analysis; one 2007 projection for coal-fire electricity-generating plants, from the U. S. DOE, forecast a cost increase of between 150 and 300 per cent and something close to a doubling of electricity prices.[9] Everyone agrees that it will be necessary for governments to create a market for carbon (in other words, treating carbon as a commodity), in which the market price is sufficiently high to justify the costs of CCS, before any commercial-scale CCS-only facilities can be built and operated.

Another significant challenge is the need for a comprehensive policy, regulatory, and legal framework for CCS in every relevant jurisdiction; for Canada, this will involve some type of joint federal–provincial framework.[10] (In addition, international agreements will be needed, through which national or regional GHG-management initiatives can be integrated – for example, emissions trading regimes and the Clean Development Mechanism under the Kyoto Protocol.) The policy dimension would cover, for example, the sharing of responsibilities as between different levels of government as well as between governments and the private sector, including possible public – private partnerships. The regulatory dimension would include GHG

[8] McKinsey & Company, *Carbon Capture & Storage: Assessing the Economics*, 2008, p. 16: http://www.mckinsey.com/clientservice/ccsi/pdf/CCS_Assessing_the_Economics.pdf.

[9] Cited in: U. S., General Accounting Office (2008), p. 23.

[10] For the U.S. see Marston & Moore (2008), Wilson et al. (2003), and Wilson et al. (2007); for a brief overview across the developed world, see International Risk Governance Council (2008) and Resources for the Future (2007).

emissions-reduction targets over time as well as health, safety, and environmental protection standards and environmental monitoring protocols. The legal dimension must include specification of ownership of the commodity and the liabilities associated with all the phases of CCS (capture, transport, storage), especially the risks of re-release or other adverse events, especially over longer time-frames, at the storage facility.

Recent contributions have advanced our understanding of three of the significant public policy issues, in a Canadian context, associated with CCS, namely: (1) economics and financing, (2) ownership and liability of the carbon captured for long-term storage, and (3) the legal framework for regulation.[11] However, the nature of the risk assessment and risk management frameworks needed for CCS in Canada have not been adequately described to date.[12] It is important that a sustained discussion of these frameworks, involving all interested parties, should be begun as soon as possible, in the context of the imminent launching of large-scale demonstration projects for CCS in Alberta.

Finally, there are challenges arising out of public awareness and acceptance of CCS, in terms of the understanding of the technologies, the policy objectives in relation to climate change issues, and the risk assessment and risk management methodologies for CCS. Citizens are likely to evaluate the prospects for CCS in the context of broad energy policy criteria, that is, the way it may affect the whole mixture and balance of future energy supply alternatives – in

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[11] See Pembina Institute and ISEEE, "Carbon Capture and Storage: Forum Proceedings" (November 10, 2008): http://pubs.pembina.org/reports/ccs-forum-proceedings.pdf; and the papers by Nigel Bankes, Mary Griffiths, and Marlo Reynolds & David Keith.

[12] The situation in the U. S. is quite different; see, e.g., the discussion of the FutureGen project in section 5, below. Also: "The United States has considerable experience injecting fluids underground – both on land and under the sea floor – for purposes of storage, recovery, and disposal" (Wilson et al. [2003], p. 3481; see also Keith et al. [2005]).

particular, the relation between fossil-fuel sources, nuclear, hydro, and "alternatives" (solar, wind).[13] As stated in a recent document from the Pembina Institute: "It is critical that CCS be considered as part of a portfolio of solutions, and that adequate attention also be paid to more sustainable, low-impact energy solutions, especially renewable energy and energy efficiency."[14]

According to the IEA's "World Energy Outlook 2008," the world's level of dependence on fossil-fuel energy in 2030 will be about the same at it is today – roughly 80% of the primary energy mix.[15] When energy mix scenarios are discussed, a key factor for many people is the distribution of various types of public subsidies across energy types. A number of governments, notably in Canada, have announced large subsidies, in the billions of dollars, for R & D on carbon capture and storage, dwarfing by several orders of magnitude the support for alternative-energy projects. Thus in this context CCS could be interpreted as a strategy to "lock in" our dependence on fossil fuels, over the long term, and thereby to inhibit the "rebalancing" of energy options. This perceived bias in favour of fossil fuel sources of energy is very likely to be a major public policy issue throughout the period of the demonstration phase of the feasibility of large-scale carbon capture and storage, and it will have to be addressed by proponents of CCS.

This paper is devoted largely to only one of these challenges, namely, the need to develop robust risk assessment methods and risk management practices for carbon capture and storage. Such methods and practices become part of the response to every one of the challenges outlined above: for example, with respect to the policy dimension, they are essential for the

[13] Palmgren et al. (2004) and Chapter 6 (pp. 117-39), "The public perception of carbon dioxide capture and storage in the UK," by S. Shackley, C. McLachlan, and C. Gough, in Gough and Shackley (2005).

[14] "The Pembina Institute's Perspective on Carbon Capture and Storage," 19 February 2009: http://alberta.pembina.org/pub/1787.

[15] http://www.worldenergyoutlook.org/docs/weo2008/WEO2008_es_english.pdf.

determination of acceptable levels of risk and thus the validation of CCS as a strategy for GHG emissions reduction; with respect to the regulatory dimension, they specify not only the risks but the cost of risk control options, thus allowing us to do risk-risk, risk-benefit, and risk-cost-benefit analyses; and finally, with respect to public awareness and acceptance, when risk assessment and risk management are carried out in credible ways, they make up an essential component of the public's responses to new technologies.

The remainder of this paper first offers a sketch of how risk management is undertaken, using what is known as an "integrated risk management framework" to explain its unique, step-by-step approach. Then two prominent, long-running and quite different Canadian cases in which a risk-based approach has been worked out in some detail – long-term storage of nuclear waste (used nuclear fuel) and prion diseases (especially so-called "mad-cow disease") – are presented. The purpose of this case-comparison exercise is to provide some real-world dimensions to the otherwise abstract discussion of risk management, and to anticipate some of the ways in which the risk management approach to carbon capture and storage is likely to unfold. The paper concludes with some comments on the nature of the full risk assessment that will be required for carbon capture and storage.

2. The Risk Management Approach.

Risk management has been called "a comprehensive, systematic process that assists decision makers in identifying, analyzing, evaluating, and treating all types of risks, both internal and external to the organization." Further, "the objective of risk management is to ensure that significant risks are identified and appropriate action is taken to manage these risks to the extent that is reasonably achievable."[16] In more concise terms, we may refer to risk

[16] Jardine et al., 2003, p. 129.

management as *an attempt to anticipate and prevent or mitigate harms that may be avoidable*.

The effort to manage risks takes place on a daily basis at every level of activity in present-day society: at the level of individuals and families, neighbourhoods and communities, urban and rural regions, large private enterprises, provincial and federal governments, and in many dimensions of international affairs for global issues. Individuals and families, for example, have a very broad range of primary responsibilities for their well-being, particularly in the areas of health and personal security; this is indicated by the fact that some three-quarters of lifetime health outcomes are related to risk factors over which individuals have some large measure of personal control. Large corporate enterprises, especially in the industrial sector, have both legal and fiduciary responsibilities to both their shareholders and governments in the areas of employee health and safety, environmental protection, and prudent financial management. Senior levels of goverments within nations have the broadest range of formal duties in this regard; through regulatory systems, for example, they set levels of acceptable risk, in occupational settings and for the general public, for literally thousands of different types of exposures to potentially hazardous substances, activities, and technologies. Even within some specific areas, such as the safety of donated blood, the risks are diverse, complex and ever-changing, requiring ceaseless vigilance on the part of the regulators (Canadian Blood Services and Héma-Québec). Finally, there is a wide variety of global risks – armed conflict, infectious diseases, environmental pollution, climate change, and many others – which can only be dealt with through concerted action at the international level.

Risk itself is defined here as “the chance of harm.” The conception of risk management as *an attempt to anticipate and prevent or mitigate harms that may be avoidable* indicates its key objectives. Seeking to anticipate events that may prove to be harmful and investigating risk control options that will at least reduce the scope of possible future harms, if they cannot be prevented entirely, is a program of action that can have very large payoffs in terms of avoiding costs that otherwise might be payable. The purchase of insurance is, of course, the best-known activity of this type. The whole of preventive medicine, such as smoking cessation and many other types of behavioural modification programs, is an exercise in risk management as defined. Environmental protection regulations are designed to prevent release of pollutants, and other types of adverse human impacts, as opposed to cleaning up after the fact.

One of the great strengths of the risk-based approach is that it can find various ways of accommodating progressively larger sets of decision inputs while maintaining an acceptable level of technical rigour. This is shown in the following schematic:

Science ⟷ (1) **Risk Management** ⟷ (2) **Public Policy**

Interface (1):
- **Risk Assessment**
- **Risk Control**
- **Risk Mitigation**

Interface (2):
- **Public Perception of Risk**
- **Risk Acceptability**
- **Public Trust**

At the interface of science and risk management, we find the technical disciplines of risk assessment, control, and mitigation, which ideally tell us what are options are, how well certain precautionary measures are likely to perform, what consequences are likely to follow from failures in risk control, and what it will cost us to achieve certain levels of risk mitigation. And yet this is now known to be only one-half of the full equation. Decisions on how to manage a whole host of major risks, such as pandemic influenza and climate change, occur in an open international arena in which a large number of interested parties, members of the general public, and governments consider their options and maneuver for relative advantage. On a purely domestic level, the same types of interveners debate narrower issues, such as vaccines, diets and obesity, and drug use; their conflicts and engagements are played out for all to see in the daily mass media. Increasingly, in all of these engagements contributions from scientists and professional risk assessors are explicitly referenced in the public debates.

Both risk assessment and management involve a high degree of technical complexity, in terms of the scientific characterization of the possible harms and how very diverse risk factors expose us to those harms. But perhaps the greatest technical challenge lies in the field of risk estimation, where the probabilities of harm for any given situation and population are calculated in quantitative terms, and where the nature of the uncertainties in that estimation are stated. For example, in Canada today, there is approximately a 1-in-8 million chance that a unit of blood will be infected with HIV. The 95% confidence interval gives us a range of uncertainty from about 1 in 20 million at the lower end of the range to about 1 in 3.6 million at the upper. This means, in effect, that we can be very much more confident that the true residual risk number is somewhere between 1 in 3.6 million and 1 in 20 million, than we can be that the number is precisely 1 in 8 million.

In response to this high degree of technical complexity, governments and others decided to set out the risk management process as a formal decision-making scheme, which breaks it down into a discrete series of specific steps in sequential fashion. These are known as risk management frameworks. The basic idea is to encourage consistency in the application of risk management [RM] techniques across the entire range of risks which much be managed. When they are applied rigorously, these schemes can provide a level of transparency, accountability, and credibility to RM decision-making that is hard to achieve by using less formal strategies and also can contribute to an enhanced level of public confidence in the management of public health risks. Public confidence can be severely tested when risk assessors are required to make predictions about the reliability of risk control measures far into the future. For carbon capture and storage processes involving sequestration of CO_2 in underground geological formations, for example, a retention period of 7000 years needs to be assured.[17]

The practice of displaying the sequential steps that should be undertaken in the process of risk management [RM] decision-making, in the form of schemata using flow-chart diagrams, began in the early 1980s. This was itself the outcome of the increasing interest in "formal" risk assessment practices, including the use of either quantitative or qualitative risk estimations. The landmark document in this regard is the famous "Red Book," *Risk Assessment in the Federal Government: Managing the Process* (US, National Research Council, 1983). On the very first page of this pathbreaking document, two themes are mentioned which continue to characterize the field down to the present day: (1) the domain of risk assessment involves "the intricate relations between science and policy"; (2) regulatory decisions about health hazards can be "bitterly controversial." Another interesting aspect of this document is its statement about the need "to ensure that risk assessments are protected from inappropriate policy influences."

The major "structural" aspect of the flow-chart design was the distinction between the poles of risk assessment and risk management (see Figure 1). The former stands closest to science and is, in fact, represented as the intermediate stage that stands between science and policy (which includes risk management decision making). Two other aspects of this early diagram became standard features in all later versions: (a) a "logical" breakdown of the components of each dimension—e.g., hazard and exposure in assessment; (b) a sequential flow from a beginning (hazard identification) to a final end-point (the risk management decision).

[17] IEA, *Prospects for CO_2 Capture and Storage* (2004), cited in Natural Resources Canada, *Canada's CO_2 Capture and Storage Technology Roadmap* (Ottawa, 2006), p. 28.

This early model was refined during the following years, as is shown in the Health Canada version, dated 1990 (see Figure 2). One of the main improvements in the later version is its more comprehensive listing of the components or inputs for all of the stages, and especially for the "options analysis" box. What is especially noteworthy in the listing of factors to be taken into account at the options analysis stage is the inclusion of "public perception of risk" and "risk acceptability," which marked a transition to later stages in the conception of the risk management process.

Analysis of past cases indicates that risk management decision-making most often fails because some critical decision inputs are either missing entirely or in part, have been analyzed inadequately, or have not been delivered when needed (Hrudey and Leiss, 2003; Hrudey & Hrudey, 2004; Leiss, 2005). Therefore, the framework requires regular re-examination, with a view to determining whether all of the necessary decision inputs are specified; in addition, the separate inputs must be specified, as clearly as possible, in a form that can be readily *integrated* with all others. For example, the analysis of psychosocial effects and their impacts must be capable of being "rolled up" and "converted" into an *operational form*, that is, into a form that can be assimilated, along with other factors, within a decision exercise.

Thus a new framework, revised in response to earlier challenges, has been designed according to a set of key requirements derived from the study of the development of risk management models in the period after 1983, in the context of the extensive case-study literature that has grown up in the same period.[18] These are:

1. The model must clearly identify one or more agencies which have "core" responsibility for a major risk issue, as well as the one agency which bears the leadership role among

[18] The new "integrated risk management framework" was developed by a research team based at the McLaughlin Centre for Population Health Risk Assessment, University of Ottawa, in the context of work on prion diseases risk management funded by PrioNet Canada; see Leiss et al., 2009 and Leiss & Nicol, 2006.

them, thus satisfying the need for clear accountability; it must also show the relation between both lead and core agencies and all other associated agencies, both domestic and international;

2. The model must use a sequential decision-making structure, and also show clearly what key inputs are required, thus satisfying the need for clarity and transparency in the decision process;

3. The model must respond to the need for *timeliness* in decision-making, by incorporating a requirement for an initial phase of informal risk estimation that precedes the later, more elaborate exercises;

4. The model must stipulate the operationalization of all decision inputs, in terms of either qualitative or quantitative measures, or both, thus permitting the integration and "rolling up" of all inputs;

5. The model must be able to show interactions with external stakeholders that are specific in nature, and are related to the generation of equally specific decision inputs;

6. The model must show clearly the points where the lead agency is responsible for communicating risk assessment results to the public and stakeholders;

7. The model must be sensitive to the dynamics of the interface of science and policy, and in particular, how the risk assessment may be "protected against inappropriate policy influences" (using the mechanism of independent and external peer review for the key analytical documents).

The integrated risk management framework, shown in a variety of schemata in Figures 3 through 6, responds to the seven requirements listed above by its inclusion of the following provisions which are not found in previous versions:

A. The first-named agency should have lead responsibility to ensure accountability throughout the entire subsequent decision process.

B. In Step 1, "risk forecasting" ("foresight") exercises are recommended as a way of implementing the "anticipate and prevent or mitigate" approach which is incorporated in the IRMF structure as a whole.

C. In Step 3, a provisional risk estimation (which may be qualitative in nature) is called for at a very early stage in the process, in those cases where early notification to potentially affected parties, and early action of a precautionary kind, may be appropriate here.

D. The "impacts estimation" phase (Step 5) specifically requires formal consideration of consequences (ideally in the form of a quantitative algorithm), including socio-economic and psychosocial dimensions, which must use standard measures (social indicators, social impact assessment, risk perception) to ensure an adequate level of methodological rigour.

E. For the first time, this framework model uses an expanded format (Figures 7-9) so as to indicate clearly the responsibilities that the core agency should discharge with respect to both inter-agency collaboration (left side) and non-governmental partners (right side), including responsibilities for timely public communication.

F. The model indicates that seeking an independent, external peer review of the risk estimation is a fundamental requirement of "best practices."

Risk-based decision-making is very much a work in progress, and even after many years in the development of robust decision-making frameworks, many substantial challenges remain.[19]

3. Risk Management of Prion Diseases in Canada.

The key characteristics of the Integrated Risk Management Framework, as shown in Figures 3 through 6, were developed in the context of reflections on Canada's experience with "mad cow disease" in the period beginning in 2003. After a brief introduction, the prion diseases case will be used to illustrate the structure and the twelve steps in the risk management framework.

Prion diseases, which affect a large number of animal species, including humans, are rapidly progressive, fatal and untreatable neurodegenerative syndromes, characterized by spongiform change in the brain. These types of diseases include bovine spongiform encephalopathy (BSE, or "mad cow disease"), Creutzfeldt-Jakob disease (CJD, the human form), and Chronic Wasting Disease (CWD, affecting deer, elk, and moose). The experience with BSE in particular presented a severe challenge, over more than two decades, to all aspects of the established risk management frameworks and practices for zoonotic diseases in more than countries in Europe, North America, and Asia. The United Kingdom, where the outbreak of BSE began, suffered huge impacts from it, which have been carefully documented in the report from a major public inquiry.[20]

[19] For the most recent review see Chapter 9, "Toward improved risk-based decision-making" (pp. 258-272), in U. S., National Research Council, *Science and Decisions* (2008).

[20] Phillips et al., *The BSE Inquiry;* Van Zwanenberg and Millstone, 2003, 2005.

Canada has been a major beef-exporting country for some time. The BSE episode, during which some seventeen cases of the bovine disease have been discovered since 2003, resulting in the closure of major export markets for Canadian beef, caused severe impacts on families involved in beef production; the economic losses probably exceed $10 billion. This experience has led to a major re-thinking of important aspects of established risk management frameworks, especially in three important dimensions: the scope of risk estimation, public perception of risk, and the evaluation of psychosocial factors in risk assessment.

Structure.

The central core in the framework describes the functions that must be performed in order to carry out credible risk management decision-making processes. These functions are assigned to the national government agencies that have the senior level of responsibility for them; however, they may also be carried out jointly with provincial agencies (as in the case of the joint federal-provincial environmental assessment panels). The exact nature of the balance between federal and provincial authority will depend on the specific set of issues to be addresses. In the prion diseases case, the overriding issues are animal and human health protection, and the federal agencies have had lead responsibility for them.

The panels to the left of the core specify the full range of other international and national government agencies which share both authority and responsibility for managing certain risks, which for prion diseases includes the World Organisation for Animal Health (OIE), WHO, the EU, and other national governments. The panels to the right seek to capture the involvement of all other interested parties, such as producers and consumers, environmental organizations, and the general public.

The twelve steps itemize the specific types of information and analysis that are required in order to produce a credible output. They can form the basis of a checklist to ensure the proper allocation of responsibilities, a basis for reporting to all other involved parties on how and when specfic responsbilities have been carried out, and as a basis for both accountability and the ongoing refinement of best practices.

Steps One through Eight: The Risk Assessment Phase.

Steps One and Two involve important, ongoing surveillance activities, the attempt to anticipate potential future threats through forecasting,[21] and ongoing review of relevant policies, laws, and regulations. Risk estimation specifies the nature of the expected harms; who may be exposed to them, including subpopulations at elevated risk; the primary risk factors (the routes through which harms affect individuals, e.g., the ingestion of infected beef); and probabilistic estimates of the likelihood of various types of harms and the potential consequences resulting from them. Step Three encourages risk managers to undertake a preliminary risk estimation, with respect to new and emerging threats, even if full information is not yet available, in those cases where cost-effective precautionary measures can be deployed.

A fuller and more formal risk estimation exercise begins in Step Four, which is intended to provide a check that all relevant risks have been identified, and at which the first major efforts in risk communication should be undertaken. Step Five expands the scope of impacts assessment beyond what has traditionally been the case, and it does so in recognition that the failure to do this in the past has resulted in serious underestimation of impacts. Step Six is a formal process that will be familiar to experienced risk managers; it is intended to lay the

[21] http://www.foresight.gov.uk/index.asp: "The UK Government's Foresight Programme and its Horizon Scanning Centre use the best evidence from science and other areas to provide visions of the future. While no one can predict what will happen, 'futures research' can help us to identify potential risks and opportunities. In this way, Foresight can assist policymakers in developing strategies to manage our future better."

foundation for a full-blown QRA (quantitative risk assessment), in which the magnitudes of the likelihood and severity of potential harms, as well as uncertainties, have been estimated using a variety of well-established formal methods. In Step Seven one proceeds immediately to the review of available risk control options, where the QRA outputs are considered in the light of established standards of acceptable risk; and, where risk reduction measures appear to be called for, cost-effectiveness criteria can be employed in order to rank them. The formal consultation process in Step Eight seeks to test the recommended options for both the risk management decision and the chosen risk mitigation strategies in consultations with affected parties and the public.

Steps Nine through Twelve: The Risk Management Phase.

Step Nine is the decision phase, where the risk manager uses regulatory and legal authority to implement risk control measures, and sets in motion an implementation phase (Step Ten) designed to achieve the specified targets. Increasingly, major risk issues have international dimensions, and so it may be desirable to coordinate, so far as possible, domestic measures in Canada with the actions of other nations and/or international bodies. For environmental risks, where impacts may be widely distributed, monitoring and compliance activities (Step Eleven) are especially important, and may involve verification protocols and audits of performance that are coordinated under international agreements. In Step Twelve, periodic evaluation, review and adjustment is carried out on an ongoing basis; and there will be occasions when new information or analysis requires one to go back to an earlier step, somewhere in the risk assessment phase, redo the calculations leading to the QRA outputs, and reconsider the risk management decision made earlier.

4. The Case of Nuclear Waste.

About thirty countries have been accumulating nuclear waste material in temporary storage facilities for many decades (in the case of the United States, since the Second World War). Most of this waste is now produced in civilian electricity-generating plants using nuclear fuel of various types. Currently, there are strong pressures to increase the share of nuclear power in the energy mix of many countries, which will also increase the number of countries that will be stockpiling the waste. Permanent storage or disposal of nuclear waste in secure underground facilities within suitable geological media is a safety requirement, due to the long life of the radioactive materials. For this reason, nuclear waste disposal is the closest analogue to the issue of the long-term sequestration of carbon dioxide. Two countries (Sweden and Finland) are the most advanced in terms of planning for such a facility.[22] Canada, through its Nuclear Waste Management Organization (NWMO), which was mandated by federal legislation in 2002, will soon begin the process of seeking a willing host community for its own site.

Canada currently has twenty-two nuclear power plants, located in three of its provinces: Ontario (20), Québec (1), and New Brunswick (1). Together they supply 14% of Canada's total electricity output (whereas hydro provides 60% and coal 25%) – but in Ontario, Canada's largest province, nuclear's share is 40%. The CANDU reactor used in all Canadian installations is a pressurized heavy-water type that uses natural (unenriched) uranium as an energy source.[23] The fresh fuel is composed of 99.28% U-238 and 0.72% U-235. When it is removed from the reactor at the end of its useful life (a period of 12 to 18 months), the used fuel bundle is both highly radioactive and hot; it is placed in a pool under water and after one year both heat and radioactivity have decreased to 1% or less of their initial values. After 100 years the radioactivity will have decreased to 0.01% of its initial level, and after about 1 million years it will approach

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[22] http://www.skb.se/default____22217.aspx (Sweden);
http://www.stuk.fi/ydinturvallisuus/ydinjatteet/en_GB/jatteet/ (Finland).

[23] http://en.wikipedia.org/wiki/CANDU_reactor

that of natural uranium.[24] After ten years the fuel bundles are removed from the pool and transferred to reinforced concrete casks on the plant site. As of the end of 2004 Canada had accumulated in temporary storage about 1.9 million used fuel bundles, representing about 36,000 tonnes of uranium. When projected to the end of the useful life of the current generation of CANDU reactors, the volume of waste will approximately double from its 2004 level.[25] Of course, should new nuclear reactors be built and operated in Canada, the volume of waste will increase, requiring either an expanded single facility or perhaps multiple operations.

The chief risk factor for used nuclear fuel is leakage of radioactive material from a storage regime into the environment, with human exposures to unacceptable levels of radioactivity occurring either directly or through environmental media, especially water. The so-called "safety case" entails a combination of technological and natural barriers to leakage, under which exposures to radioactivity from waste remains within acceptable limits for very long time frames – a minimum of 10,000 years, sometimes as long as 100,000 years, and even (as mandated in the United States) up to 1 million years.[26] All of the regimes proposed so far by various countries which hold nuclear waste in interim storage, including Canada, involve some kind of "multi-barrier" approach: First, the waste is sealed inside large stainless-steel containers; second, those containers are encased in copper, which resists corrosion; third, the steel-copper containers are placed inside cavities that are filled with bentonite clay, which resists water entry; fourth, these cavities are excavated out of a suitable geological medium such as unfractured granite, found widely in the Canadian Shield, at a depth of 500 metres or so.[27]

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[24] Nuclear Waste Management Organization, *Choosing a Way Forward: The Future Management of Canada's Used Nuclear Fuel* (2005), p. 341: http://www.nwmo.ca/Default.aspx?DN=1487,20,1,Documents

[25] *Ibid*., pp. 350-1.

[26] See the excellent article at: http://en.wikipedia.org/wiki/Yucca_Mountain

[27] For Canada, see: http://www.nwmo.ca/Default.aspx?DN=e5ed2d5e-0d75-40e1-b3e2-3c67f955ae30

When the NWMO reviewed its risk management options in 2004, it was obliged by its government terms of reference to include three "technical" methods of permanent waste storage in its assessment: (1) leaving the waste at the reactor sites; (2) moving the waste to a centralized facility, with storage either above-ground or shallow underground; (3) moving the waste to a centralized facility and storing it deep underground in a suitable geological medium.[28] The group which was given the responsibility of finding an acceptable method for ranking these options, in order of priority, selected multi-attribute utility analysis (MAU) for this purpose.[29]

The real key to the whole exercise lies in the choice of objectives that must be satisfied by any technical solution. (A more precise way of expressing this is to ask: How well will a specific solution perform, within one of the chosen time-frames, with respect to a specific objective?[30] When asked in this form, the answer can be given by means of a score along a scale, say 1–100.) Here is where the integration of the social and the technical dimensions takes place, as can be seen in the final list of eight objectives chosen by consensus of the assessment team members:

1. Fairness (including inter-generational fairness);
2. Public health and safety;
3. Worker health and safety;
4. Community well-being;
5. Security (e.g., against terrorist attack);
6. Environmental integrity;
7. Economic viability;
8. Adaptability.

A key decision in the MAU method is to initially assign all objectives equal priority; at a later point, weighting exercises are performed as a test of robustness. The length of time specified in

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[28] Nuclear Waste Management Organization, *Assessing the Options* (June 2004), chapter 4: http://www.nwmo.ca/Default.aspx?DN=1091,1090,199,20,1,Documents.

[29] See the account of MAU at: http://www.prioritysystem.com/glossary1c.html#mua.

[30] See the special issue of the journal *Risk Analysis* (Vol. 19, no. 5 [October 1999]) on "Performance Assessment for Radioactive Waste Disposal."

the safety case (minimum 10,000 years) means that timelines must be dealt with explicitly. In this case, the group decided to score the expected performance of each option twice, that is, as near- and far-term solutions (more precisely, about 0-200 years and 200+). The final result is a set of "situations" or matrices: 3 [technical solutions] x 2 [time-frames] x 8 [objectives] = 48 scores (except that the objective of fairness was not divided into two time-frames.) Each of the resulting 45 situations was individually scored, on the relative performance scale of 1-100, by each of the team members (collectively, therefore, with nine team members there were 405 separate scores).

A dedicated software program keeps track of the scoring and "rolls up" the results at the end: The final tally showed a strong preference for the deep underground storage option. It is possible that this type of method could be used for ranking decision options for carbon capture and storage.

5. Risk Assessment for Carbon Capture and Storage.

A 2006 document from Natural Resources Canada, *Canada's CO_2 Capture and Storage Technology Roadmap*, states (p. 58): "The top priority for storage research is the confirmation that CCS is a safe, reliable and environmentally beneficial practice for long-term CO_2 storage ([on] the order of thousands of years)." Such a confirmation can only be derived from arraying evidence and judgment within careful, comprehensive, and credible risk assessment and risk management frameworks. This effort has not yet been started in Canada.

The International Energy Agency conducted a very preliminary risk assessment workshop in July 2004 (IEA2004b). There are several good presentations, in the form of

PowerPoint slides, available on the Web that illustrate the risks associated with CCS.[31] According to the important article by Damen et al. (2006, p. 290): "Risk assessment is a first step in a strategy to set up management and control measures to minimise risks of underground CO_2 storage. Also, it helps to facilitate the formulation of standards and regulatory frameworks required for large-scale application of CCS." They further recommend (p. 311) that "a common risk assessment methodology able to assess long-term effects of underground CO_2 storage should be further developed." Finally, they comment (p. 305): "The lessons to be learned from underground disposal of nuclear waste should be found in the area of risk assessment methodology, monitoring, and public outreach (specifically what went wrong in this process)."[32] More recently a team at Lawrence Berkeley National Laboratory produced a short document entitled "Carbon Sequestration Risks and Risk Management" (Price, 2007).

A report of the Intergovernmental Panel on Climate Change (IPCC, 2005) offered an early discussion of the major risks and risk factors associated with CCS, dealing separately with capture, transport, and sequestration in land-based geological formations and deep ocean ecosystems. The major risks identified in this report, and others, are as follows[33]:

1. <u>CO_2 Capture:</u>
    a. Occupational risk (chronic, and acute cardiovascular and respiratory risk at concentrations exceeding 3%);
    b. Asphyxia at concentrations above 15%.

2. <u>Transport:</u>
    a. Acute risks as above, due to leakage from pipeline failure (hazards to humans and wildlife), especially in low-lying areas;
    b. If H_2S is included in the pipeline mixture, acute risk at 100ppm;
    c. Ships (tankers) and terminals: accidental release through collision.

3. <u>Storage – Land:</u>
    a. Local effects (e.g., elevated concentrations in near-surface environment);

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[31] See Selmer-Olsen (2006), Brockett (2007), Dawes (2007) and Rohner (2007).

[32] For "what went wrong" in nuclear waste siting see Flynn and Slovic (1995).

[33] See sections 3.6.3, 4.4, 5.7, and 6.7.

   b. Leakage by vertical transport into the atmosphere;[34]
   c. Leakage by vertical or lateral transport into aquatic ecosystems or underground drinking-water reservoirs.

4. Storage – Oceans: not included (unlikely to be approved due to general prohibitions against ocean disposal).

Another formulation of the set of risks, using different terminology, and referring only to the storage phase, is as follows:[35]

A. Global:
   - Release of CO_2 to the atmosphere

B. Local:
   1) CO_2 in atmosphere or shallow subsurface:
      a. Suffocation of humans or animals above ground
      b. Effects on plants above ground
      c. Biological impacts below grounds (roots, etc.)

   2) CO_2 dissolved in subsurface fluids:
      a. Mobilization of metals or other contaminants
      b. Contamination of potable water
      c. Interference with deep-subsurface ecosystems

   3) Displacement:
      a. Ground heave;
      b. Induced seismicity;
      c. Contamination of drinking water by displaced brines;
      d. Damage to hydrocarbon or mineral resources

U. S. "FutureGen" Risk Assessment and Environmental Impact Statement (2007).

The FutureGen Power Plant is conceived as a nominal 275MW, near-zero-emissions facility producing hydrogen from coal to generate electricity; it would be designed to remove 90% of the

[34] Leakage may occur as a result of failures in injection boreholes or through undocumented or abandoned wells; slow or quick release through failure of cap-rock seals; from existing faults due to increased pressure, or from induced seismicity resulting in new fracturing and fault activation. There is a nice graphic in Figure 2-1 (PDF file, p. 25) of the "FutureGen" risk assessment (see next section).

[35] Wilson et al. (2003), p. 3477. Wilson et al. (2007), pp. 5945-6, write: "Effective regulatory and legal frameworks for GS [geological sequestration] must ensure that the activity is both safe and effective. Deployment will require development of a comprehensive risk characterization and management strategy for GS that both responds to existing requirements and addresses risks not covered by the current regulatory and legal frameworks." See also the long list of research requirements in Table 1, p. 5947, as well as the discussion of policy implications on pp. 5949-50; altogether, this article provides a first-rate guide on regulatory considerations for CCS. The demand to push ahead in this area is especially urgent for Canada, since the risk assessment framework for CCS is at present quite undeveloped here; Wilson et al. (2008) comment on the urgency.

coal's carbon and 99% of its sulphur (the latter to be processed for sale), capturing between 1-2.5MMT/year of CO_2 for sequestration.[36] Four separate candidate sites, two in Illinois and two in Texas, were considered in the environmental assessment. Some idea of the scope of the project analysis undertaken by the U. S. Department of Energy is given by the sheer size of the final published reports – close to three thousand pages.[37] The risk assessment report itself runs to 400 pages, and this document provides what is, to the best of my knowledge, the only published presentation to date of a comprehensive risk assessment methodology for CCS.

To begin, the twin charts dealing separately with pre-injection and post-injection scenarios outline the environmental pathways for three broad types of risk: acute and chronic human health risk and ecological risk.[38] The site characterization summary for the four sites includes approximately thirty different parameters, dealing with the nature of surface ecosystems (aquatic and terrestrial ecology), subsurface features, seismicity, and the geologic features of the seal and reservoir in the deep underground zone (target area).[39] An overview of the risk assessment approach is provided for both the pre- and post-injection scenarios,[40] which consists of the following steps:

1. Specifying health and ecological toxicity criteria for both scenarios;
2. Failure modes, release scenarios, exposure analysis, and consequences analysis for the pre-injection scenario;

[36] The Bush administration cancelled the project in February 2008, just after Illinois was chosen as a site instead of Texas, but as of early 2009 there are attempts in Congress to revive it (see Kimberly Kindy, "New Life for 'Clean Coal' Project, *The Washington Post*, 6 March 2009: http://www.washingtonpost.com/wp-dyn/content/article/2009/03/05/AR2009030502138_pf.html).

[37] The Environmental Impact Statement is in three volumes, totalling 2,332 pages, and its separate Summary is 152 pages; URLs for the electronic copies of all of the reports are given in the Bibliography.

[38] FutureGen Risk Assessment, Figures 2-2 and 2-3 (PDF file, pp. 26, 27).

[39] FutureGen Risk Assessment, Figure 2-5 and Table 2-1 (PDF file, pp. 31-34); the site that was chosen (Matoon, Il.) is described on pp. 50-57.

[40] FutureGen EIS, Volume I, Appendix D (Risk Assessment Methodology) and FutureGen Risk Assessment, Section 4.2 (PDF file, pp. 91ff.).

3. Leakage pathways and exposure and consequences analyses for the post-injection scenario. The four post-injection leakage pathways evaluated are: upward leakage through caprock and seals; release through faults; migration into non-target aquifers; and upward migration through wells. The exposure analysis considers both human and ecological receptors.[41]

A comprehensive Risk Summary is summarized in nine tables, broken down (for human health impacts) into adverse effects, irreversible adverse effects, and life-threatening adverse effects; predicted probabilities of release for all scenarios, uncertainties, and data gaps are specified.[42]

Impact Assessment of CCS in the European Union.

At the beginning of 2008 the European Union issued a guidance document for assessing the impacts of CCS across all three of its principal dimensions, in which there is some discussion and quantitative estimation of hazards and risk factors (e.g., accidental releases of CO_2), but not yet a full QRA (including uncertainties). However, this does seem to be the most complete review to date of the entire range of considerations related to the hazards associated with CCS, for example:[43]

1. Hazards are specified for each of the major components (capture, transport, storage) in a systematic way;

2. There is an explicit recognition that risks associated with the increased energy generation required for CCS must be included;

3. A storage site selection process, including use of a scientific panel to certify the safety case for any site, is outlined;

4. Financial security mechanisms, related to the long duration of the project (similar to those applicable to nuclear waste storage) are reviewed.

[41] Release scenarios: FutureGen Risk Assessment, Section 5.3 (PDF file, pp. 139ff.).

[42] FutureGen Risk Assessment, Section 6.0, Risk Screening and Performance Assessment (PDF file, pp. 223ff.).

[43] European Union (2008b), section 7.6.3, "Societal risks and impacts of CCS deployment," and following, pp. 67-76; and annexes II – VIII, pp. 90-120.

There are one or two good independent discussions of regulatory needs in the EU context, as well as an excellent, brief overview document on risk assessment and management in the EU context.[44]

Risk Management.

As noted briefly in Section 2 of this paper, risk management moves the outputs from the risk assessment into a decision-making process. Those outputs represent a detailed estimation, in quantitative terms, of the probabilities that certain types of harms will occur, under specific circumstances, and the full range of consequences (ecosystem and human health, monetary, social impacts) that might result, if they should occur. With this information in hand, and with the objective to *anticipate (and prevent or mitigate) serious potential harms before they occur*, risk management undertakes:

1. To review and evaluate the level of risk and risk acceptability, according to criteria that are presumed to have wide public confidence;
2. To consider the availability of risk control options for risk reduction, as set out in risk-risk, risk-benefit, cost-benefit, and risk-cost-benefit analyses;
3. To communicate effectively and transparently, with all affected stakeholders, about the decisions and decision process;
4. To establish robust protocols for monitoring of expected results, the utilization of new knowledge, and the implementation of corrective measures where necessary.

The "integrated risk management framework" (IRMF) illustrated in Figures 4-6 is designed specifically to move away from the usual "black box" character of the risk-based decision-making process by requiring risk managers to provide a higher degree of transparency in all stages of that process. One of the greatest advantages of increased transparency is the encouragement it supplies for continuous improvement and the adoption of the latest best practices. It can also serve as the basis of a "checklist" to document the timely completion of

[44] ECN, "Choices for regulating CO_2 capture and storage in the EU," 2007; World Resources Institute, "Impacts of EU and international law on the implementation of carbon capture and geological storage in the European Union," 2005; cf. Mace et al. (2007).

necessary decision inputs, thus reducing the risk that important inputs may be overlooked and establishing a more rigorous form of retrospective performance evaluation.

Operational details for decision criteria vary according to the nature of each major type or set of risks to be assessed and managed. So far as carbon capture and storage is concerned, the literature published to date indicates that there are strong similarities to technologies and practices, developed for other purposes, which provide a firm basis for the risk assessment of CCS. On the other hand, there are also certain important and unique aspects to the risk profile for CCS that demand the application of new criteria and practices designed specifically for this case. In addition, the promise represented by CCS – to be one of the most significant mitigation strategies for controlling GHG emissions – means that CCS is likely to have, in Canada and elsewhere, a high public profile. This expectation suggest that, as large demonstration projects get under way, no effort should be spared in order to put in place credible and transparent risk assessment and risk management frameworks for CCS as soon as possible.

Figure 1:
"Red Book" (Risk Assessment in the Federal Government: Managing the Process, 1983)

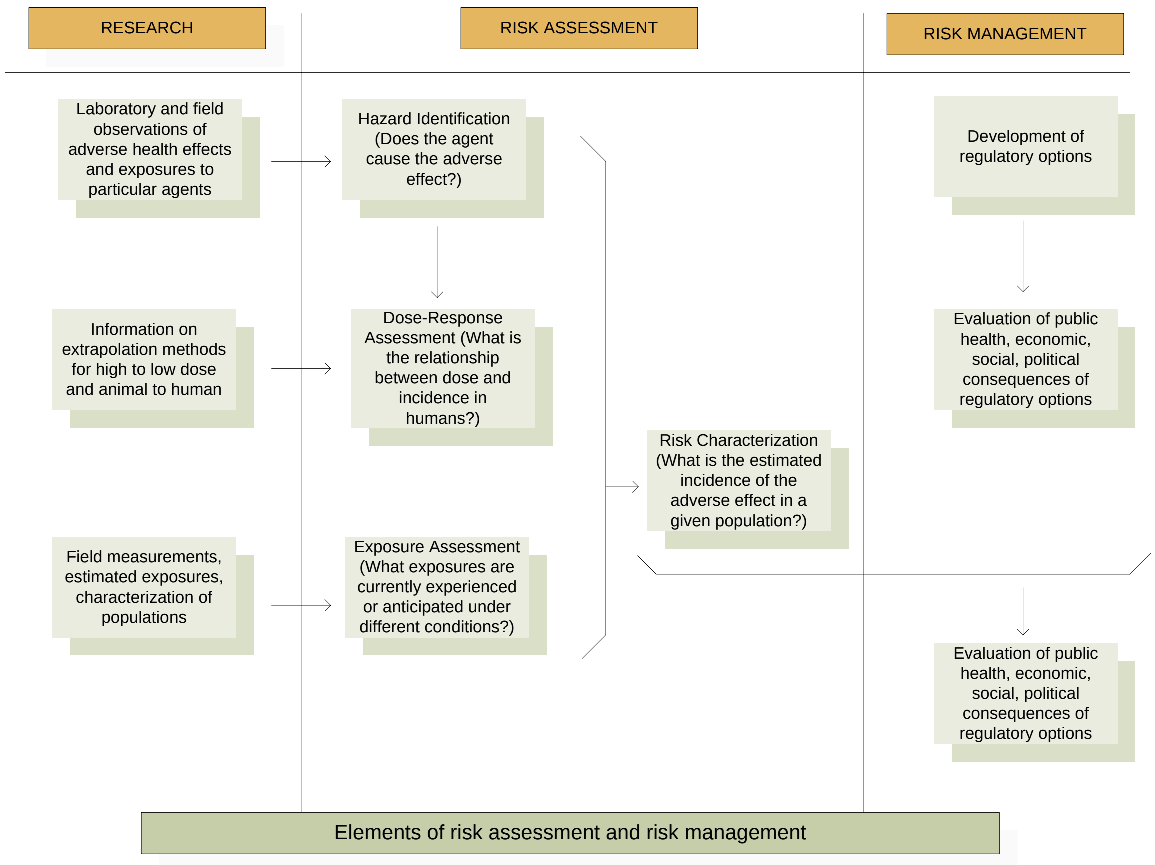


Figure 2:
Health Canada's Risk Assessment and Risk Management model (mid-1980s), as shown in Leiss and Krewski (1989)

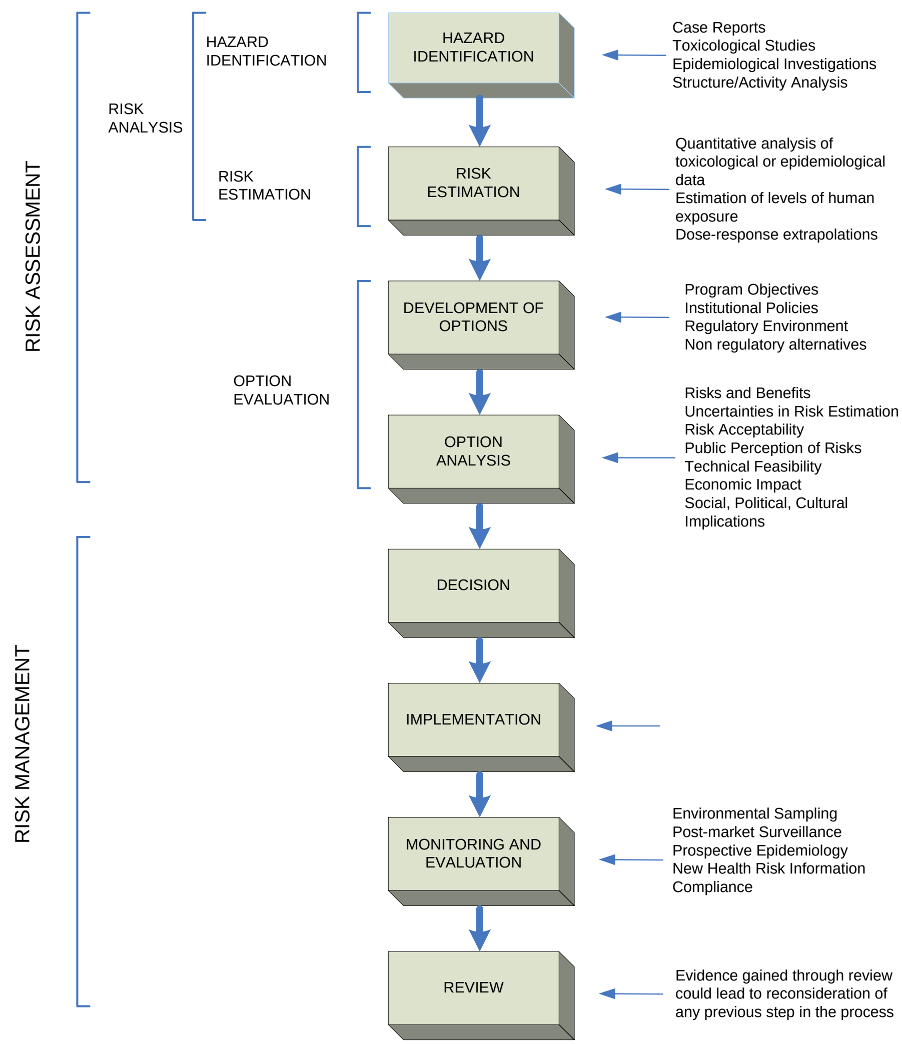


Figure 3: IRMF-1

From: W. Leiss et al. (2009)

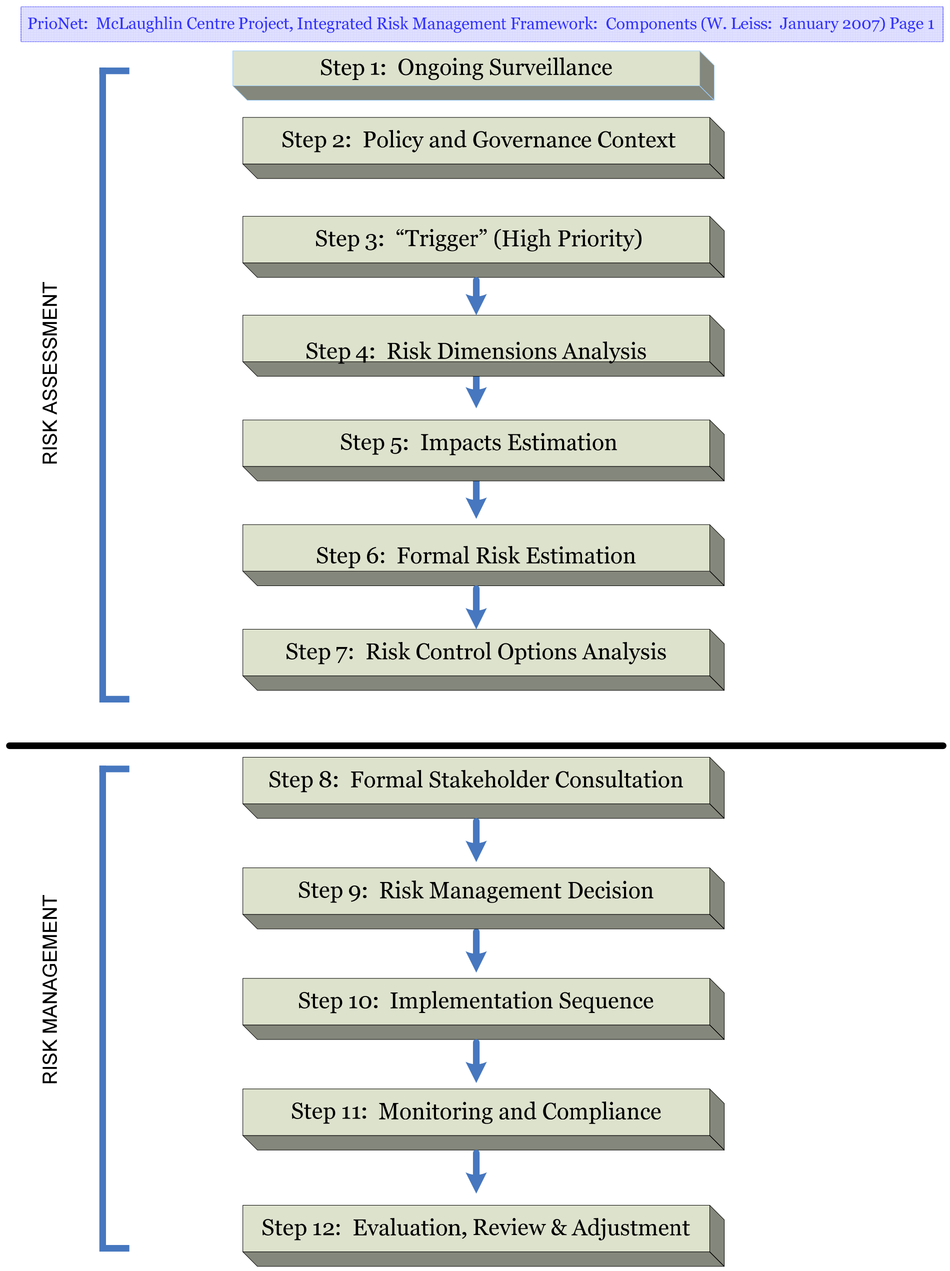


Figure 4: IRMF-2

From: W. Leiss et al. (2009)

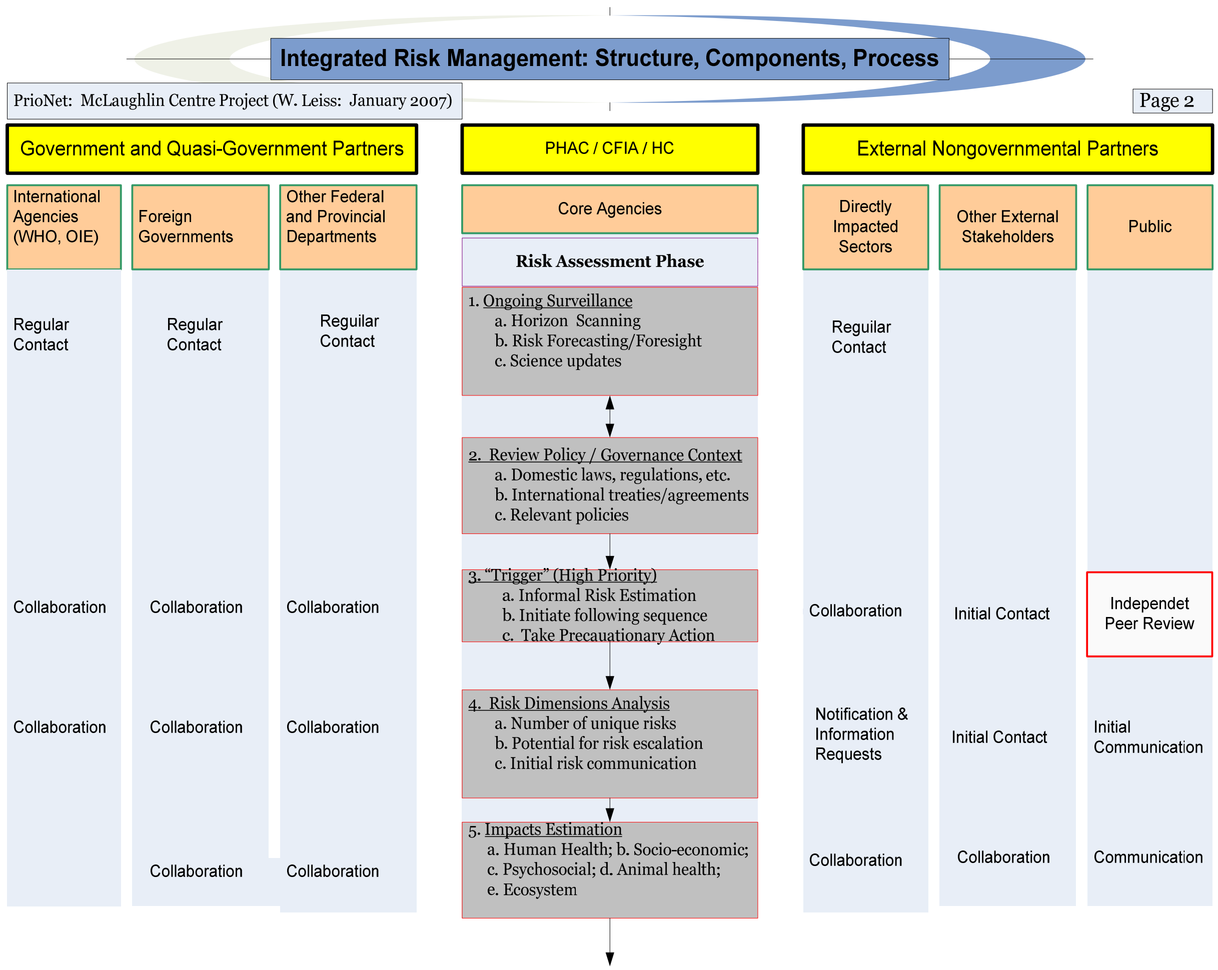


Figure 5: IRMF-3

From: W. Leiss et al. (2009)

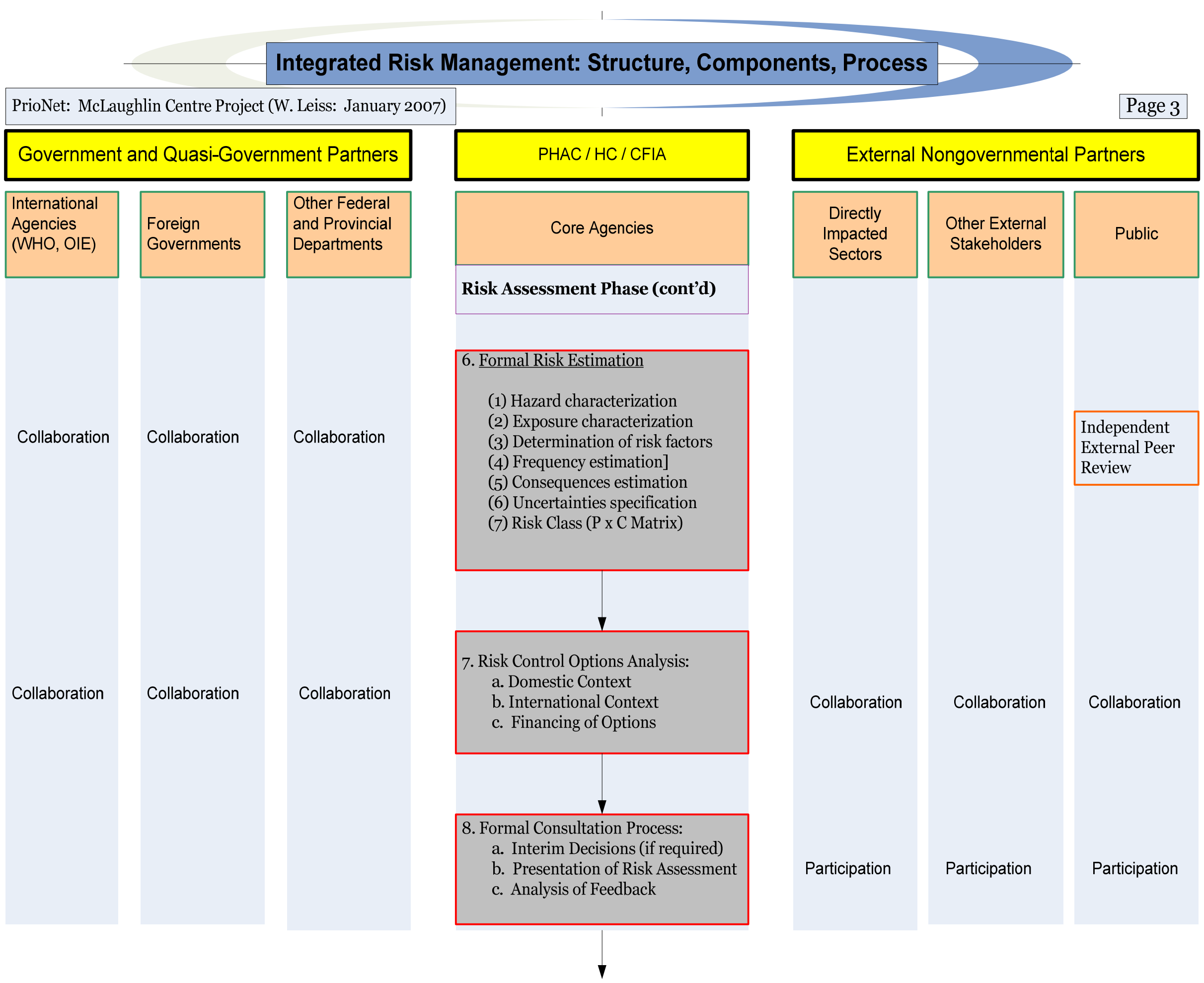
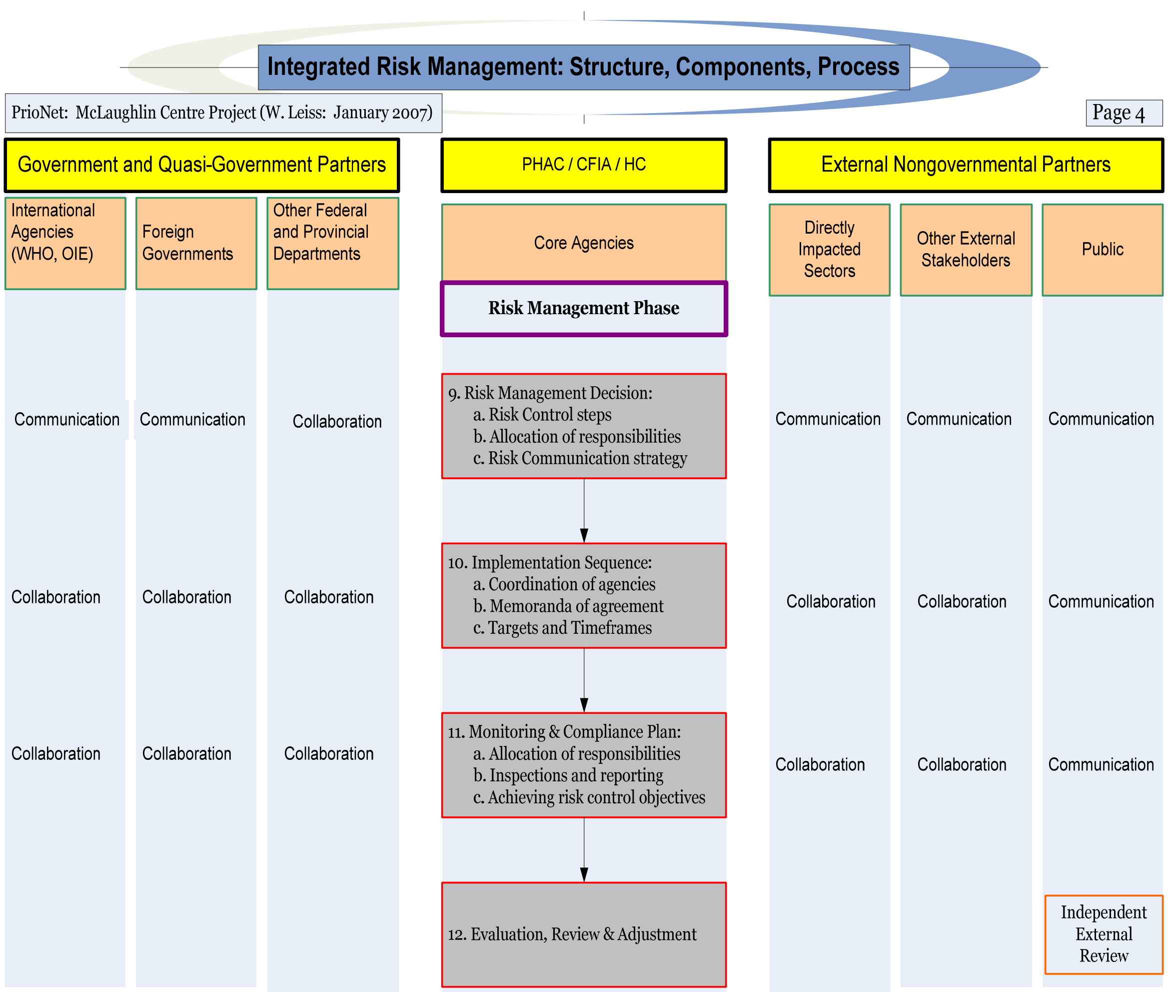


Figure 6: IRMF-4

From: W. Leiss et al. (2009)



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Main webpage on CCS: http://ec.europa.eu/environment/climat/ccs/index_en.htm

Overview: http://ec.europa.eu/environment/climat/ccs/work_en.htm

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