r

SSI Rapport
SSI report

2002:14 GRAHAM SMITH, JOAN MERINO AND EMMA KERRIGAN

Review of C-14 inventory for the SFR facility

Statens strålskyddsinstitut
Swedish Radiation Protection Authority

AUTHOR/ FÖRFATTARE: Graham Smith, Joan Merino and Emma Kerrigan.

DIVISION/ AVDELNING: Department of Waste Management and Environmental Protection/ Avdelningen för Avfall och Miljö.

TITLE/ TITEL: Review of C-14 inventory for the SFR facility/ Granskning av C-14-inventariet i SFR.

SUMMARY: The Swedish Radiation Protection Authority (SSI) is currently reviewing SKB's continuing assessment for disposal of radioactive waste to the SFR facility at Forsmark. Among the wastes disposed are reactor operating wastes. Among the relevant radionuclides is C-14, which is relatively difficult to measure and to control because of its mobility. This report documents a review of the C-14 inventory material submitted by SKB for the SFR-facility, to determine its validity and comment on the appropriate assumptions for C-14 content of wastes due to be disposed of to the SFR. The review is based on information provided by SSI as well as other relevant international experience.

Conclusions are drawn upon: the chemical form of the C-14 in the waste from BWRs and PWRs; the production rate of C-14 in BWRs and PWRs and quantification of the source term in the IEX waste; the distribution of the C-14 in the IEX waste from BWR between the resins used for treatment of the primary cooling water and the resins used for treatment of the condensate water; quantification of the uncertainties. A suggestion is made that the C-14 inventory could be better developed based upon a mass balance assessment of all the C-14 produced in reactors, and its ultimate fate in effluent and solid wastes, taking account of the reactor specific operational factors identified in the review as relevant to C-14 inventory assessment.

SAMMANFATTNING: Statens Strålskyddsinstitut granskar för närvarande SKB:s förnyade säkerhetsanalys för slutförvaret för radioaktivt driftavfall, SFR 1, vid Forsmarks kärnkraftverk. Vid SFR 1 deponeras driftavfall som uppstår vid driften av de svenska kärnkraftverken. En viktig radionuklid i detta sammanhang är kol-14, dels för att den är relativt svår att mäta, dels på grund av dess rörlighet i slutförvarsmiljön. I denna granskningsrapport kommenteras utgångspunkterna för och giltigheten i SKB:s rapporterade kol-14-inventarium i avfallet som deponeras i SFR 1. Granskningen baseras på information tillhandahållen av SSI och även annan relevant internationell expertis.

I rapporten dras slutsatser om produktionshastigheten och den kemiska formen hos det kol-14 som genereras i kokarvattenreaktorer (BWR) respektive tryckvattenreaktorer (PWR) samt fördelningen av kol-14 i jonbytarmassor från rening av primärvattnet respektive kondensatvattnet i BWR. Slutligen uppskattas osäkerheterna. I rapporten föreslås att en massbalansstudie bör genomföras för allt det kol-14 som genereras i reaktorerna. Studien bör utvärdera om det kol-14 som produceras släpps ut eller hamnar i det fasta avfallet. Massbalansstudien bör ta hänsyn till de reaktorspecifika faktorer som identifieras i rapporten.

SSI rapport : 2002:14
augusti 2002
ISSN 0282-4434

Statens strålskyddsinstitut
Swedish Radiation Protection Authority

Förord

Svensk Kärnbränslehantering AB (SKB) redovisade sommaren 2001 en förnyad säkerhetsanalys för slutförvaret för radioaktivt driftavfall vid Forsmark, SFR 1, etapp 1. I SSI:s och Statens kärnkraftinspektions (SKI) driftmedgivande från 1988 och 1992 anges att SKB ska lämna en sådan uppdaterad analys till myndigheterna minst var tionde år så länge som förvaret är i drift. SSI och SKI har i sin gemensamma granskning av SKB:s säkerhetsredovisning för SFR 1, framförallt vad det gäller förvarets skyddsförmåga efter förslutning, tagit hjälp av oberoende internationella experter som detaljgranskat viktiga delar av SKB:s säkerhetsredovisning.

Denna rapport redovisar en av flera konsultgranskningar av SKB:s säkerhetsredovisning för SFR 1, som utförts på uppdrag av SSI. Granskningen fokuserar på en av de viktigare radionukliderna i SFR 1, nämligen kol-14 som är en långlivad nuklid som bildas vid reaktorerna under drift. Beroende på dess kemiska form kan kol-14 vara mer eller mindre rörlig i den miljö som råder i slutförvaret. Radionukliden är relativt svårmätt och därför bestäms normalt inte halterna i avfallet på annat sätt än genom indirekta metoder. I denna granskningsrapport kommenteras utgångspunkterna för och giltigheten i SKB:s rapporterade kol-14-inventarium i avfallet som deponeras i SFR 1.

Arbetet har letts av Graham Smith vid konsultföretaget ENVIROS QUANTISCI i England och utförts tillsammans med Joan Merino och Emma Kerrigan. Författarna svarar själva för innehållet i denna rapport. SSI:s samlade bedömning av SKB:s redovisning kommer att redovisas i en särskild granskningsrapport som tas fram gemensamt av myndigheterna SSI och SKI.

Contents

1 Introduction

The Swedish Radiation Protection Authority (SSI) is currently reviewing SKB's continuing assessment for disposal of radioactive waste to the SFR facility at Forsmark. Among the wastes disposed are reactor operating wastes. Among the relevant radionuclides is C-14, which is relatively difficult to measure and to control because of its mobility. Special studies of C-14 waste management have therefore been carried out over the years; see e.g. Bush *et al.* [1984].

Currently questions arise concerning the level of C-14 expected to arise in light water reactor (LWR) operating wastes, particularly the IEX (ion exchange) resins. Work by SKB suggests that previous assumptions about C-14 being lost to effluent waste streams may no longer be appropriate. However, the corollary of an increase of C-14 in solid operating wastes does not appear to have been recognised. In addition, the C-14 in PWR (pressurised water reactors) operating wastes, as opposed to BWR (boiling water reactors) wastes, appears to be primarily in an organic rather than inorganic chemical form. Organic and inorganic C-14 may be differently mobile within a waste disposal facility.

This report documents a review of the C-14 inventory material submitted by SKB for the SFR facility, to determine its validity and comment on the appropriate assumptions for C-14 content of wastes due to be disposed of to the SFR. The review is based on other relevant international experience as well as information provided by SSI, including:

- relevant extracts from SKB's final safety assessment of the SKB-facility, submitted in June 2001, concerning the source term of C-14 in the safety analysis [SKB, 2001];
- relevant extracts from SKB Report R-01-03 (draft version) [Riggare & Johansson, 2001], Reference Waste Inventory for the SFR;
- relevant extracts from SKB report of the reference inventory of the SFL 3-5 facility [Lindgren *et al.*, 1998];
- SSI project report Reduction of C-14 releases from nuclear power plants [Torstenfelt & Olsen, 1996];
- Characterisation of C-14 generated by the nuclear power industry. Electrical Power Research Institute Report EPRI TR-105715, Palo Alto, California USA [EPRI, 1995].
- Part 1 of the SKB report, Source terms, isolation and radiological consequences of C-14 waste in the Swedish SFR repository [Hesbol *et al.*, 1990].

The review focuses on clarifying the validity of the assumptions concerning the source term of C-14 in IEX resins deposited in the SFR facility, specifically:

- the chemical form of the C-14 in the waste from BWRs and PWRs;
- the production rate of C-14 in BWRs and PWRs and quantification of the source term in the IEX waste;

- the distribution of the C-14 in the IEX waste from BWR between the resins used for treatment of the primary cooling water and the resins used for treatment of the condensate water;
- quantification of the uncertainties.

Section 2 reviews the material supplied by SSI and Section 3 reviews additional material. Appendix A provides the results of a literature search. Conclusions are provided in Section 4. References are given in Section 5.

2 Review of SSI supplied material

Each of the items referred to in the introduction is reviewed for its relevance to justification of the SKB assumed SFR C-14 inventory. Reference is made to other material where this supports or contradicts the SKB assumptions.

SKB [2001]: The key inventory issue noted here is the assumption that 10 % of the C-14 in IEX resin and in similar wet wastes is in organic form, based on an averaging of BWR and LWR contributions and bearing in mind that about only 5 % is organic in the BWR contribution but 50 % in the PWR contribution. This makes approximate sense given there are eight BWRs and three PWRs, but it does not appear to take account of other reactor specific factors mentioned below. In addition, it is stated that doses are dominated by C-14, but that the C-14 inventory is probably over-estimated. The total C-14 and the chemical form are noted as uncertainties.

Riggare & Johansson [2001]: The C-14 given to be present for the SAFE project calculations, for the conservative inventory, is 2.6E13 Bq, only a small fraction of the facility limit of 1E16 Bq[1]. The realistic inventory is said to be about an order of magnitude lower, both in general and for C-14 in particular. About 75 % of C-14 is present in the silo, and most of the rest in the BTF and BTA, in roughly the same proportions for the conservative and realistic inventories.

For most waste streams there is little direct measurement information on C-14. For most waste streams the inventory of C-14 is assumed to be correlated to Co-60. Uncertainties in the use of these correlations are mentioned but not discussed directly in relation to C-14 and Co-60. We note that a correlation may exist, but it is not obvious why there should be one. Although both C-14 and Co-60 arise primarily as a result of neutron activation, the relevant activated elements are different and the products have significantly different chemical behaviour and so would be distributed among operating wastes differently, including effluent and solid waste arisings. Use of correlations has been investigated within a project for the European Commission [Noe *et al.*, 1998], and this is discussed below.

The summary information presented for waste streams is summed over station, so it is not easy to distinguish the BWR sources (Barseback, Forsmark, Oskarshamn reactors and Ringhals 1) from the PWR sources, (Ringhals 2, 3 and 4). Apart from differences for these main reactor types, the chemical form in reactor operating wastes will also in part depend on how the reactor is operated, further discussed below. These details are not provided in the material reviewed and so the implications for C-14 inventory assumptions cannot be reviewed.

It is made clear that the major C-14 sources are the operating wastes from the reactors, although CLAB and Studsvik also produce non-trivial inventories of C-14.

Overall, it is not easy to determine from the material supplied what the more likely abundance is of the different chemical forms of C-14 in wastes going to SFR.

[1] Y-90, the daughter of Sr-90, is not included in the inventory. The Sr-90 cannot be disposed without the Y-90. So at the time of closure there would be an additional amount of Y-90 present, in secular equilibrium with the Sr-90. Thus, if Y-90 were included, then the total would appear to exceed the 1E16 Bq facility limit. The same point arises with other relatively short-lived daughters.

Lindgren *et al.* [1998]: This report is intended to provide the justification for the SFL 3-5 inventory. It is clearly stated that the study does not include an investigation to prove (or test) if there are correlations between the key radionuclides and the selected radionuclides. C-14 is said to be produced by neutron activation of N-14, O-17 and C-13. This is consistent with Bush *et al.* [1984].

We note that Bush *et al.* [1984] provide estimates of C-14 produced in fuel, cladding and cool ant in BWRs and PWRs. These authors noted that overall production is significantly dependent upon the assumption for nitrogen level in fuel, which may range from 5 to 75 ppm. The nitrogen content of coolant water was assumed to be very low and so this source reaction was ignored. Nevertheless, the relative significance of the different production reactions mentioned above depends on the assumptions for nitrogen contents, which may be quite variable in different systems. While C-14 production in fuels, cladding and structural materials dominates overall C-14 production, C-14 arisings in operating wastes, such as IEX resins, would normally be dominated by production in coolant, due to the O-17 neutron reaction. Bush *et al.* [1984] estimates of production in coolant range from 1.9E11 to 4.2E11 Bq/GW(e)y for BWRs and from 1.1E11 to 2.3E11 Bq/GW(e)y for PWRs[2]. EPRI [1995] provide more recent calculations, i.e., not based on measurements, giving a value of 5.4E11 Bq/GW(e)y in coolant for BWRs and 2.2E11 Bq/GW(e)y in PWRs, i.e. very similar to those given in Bush *et al.* [1984]. However, they included nitrogen dissolved in coolant water and so essentially agree that dissolved nitrogen is not very important.

Lindgren *et al.* [1998] go on to say that the CRUD[3] correlation factor for C-14 is very uncertain with values reported ranging from very low values, less than1E-6, up to near unity in one study from the USA, and values from 1E-4 to 1E6 *(sic)* in Thierfeldt & Deckert [1995] for German and Japanese data. These authors report the wide ranges of correlation factor mentioned above. They also conclude that it cannot be determined how differences in water chemistry or variations in plant design between various countries influence the C-14 contents in waste streams. This conclusion would suggest that it would be hard to justify applying correlations found in other countries to Swedish reactors.

Lindgren *et al.* [1998] confirm that there are no correlation data for Swedish reactors[4], and justify the value of 1E-3 on the basis that 1 % of C-14 in coolant water will be found in the operational (solid) waste. This assumption itself is not justified but is perhaps assumed to be a reasonable assumption based on knowledge of proportions of C-14 discharged in effluents. EPRI [1995] suggest that approximately 80 % to 95 % of the C-14 produced (in coolant) is discharged as gaseous waste, with the remainder going to a variety of the operating solid waste streams.

Lindgren *et al.* [1998] go on to discuss chemical form. They point to the differences in proportions of organic and inorganic C-14 produced in BWRs and PWRs, with a high proportion being organic in PWRs and a small proportion in BWRs, though this may be higher if hydrogen injection is employed at the BWR. These suggestions are supported by EPRI [1995]. Like EPRI [1995], Lindgren *et al.* [1998] also suggest that 5 % to 15 % of BWR C-14 is released to atmosphere (appendix F), attributing to Torstenfelt, 1996, probably actually Torstenfelt & Olsen

---

[2] These estimates do not allow for any C-14 activity in coolant arising from fuel failure.

[3] A different correlation factor, 5E-4, is adopted for 'Induced Activity'. Since nearly all the C-14 is produced in activation (apart from a small fraction arising from tertiary fission) it is hard to see what is meant by 'induced' here, as distinct from CRUD activity. It appears to refer to activity activated in structural metals, i.e., it is not related to the prime concern in this report, which is activity activated in coolant or which gets into coolant having been 'induced' elsewhere. Swedish data are provided for a correlation for C-14 in the activated metals, near to 1E-3, but this has little to do with the current interest in a factor for coolant or for operating wastes.

[4] They cite Thegerström & Hard [1981], reporting a value of 1E-3 in Swedish operational waste, but apparently this is based only on the same assumption that 1 % C-14 will be retained in solid waste [personal communication from A Wiebert, SSI, 5 February 2002.].

[1996]. It is hard to see how this fits with an assumption of adopting a correlation factor of 1E-3, on the assumption that this corresponds with 1 % of C-14 in coolant ending up in operating waste. None of these authors has specifically mentioned levels or proportions of C-14 in liquid effluent. Is that where the other 4 % to 14 % is thought to go? Or were Lindgren *et al.* [1998] talking about total C-14 production when referring to 1 % going to operating waste, and only coolant C-14 production when talking about the percentage of C-14 going to atmosphere? The difficulty arises in that the technical measurements, which can provide good data, are limited to relatively few examples, and the results cannot be readily extrapolated to other circumstances.

Torstenfelt & Olsen [1996]: These authors suggest that nitrogen is important in C-14 production in coolant for PWRs, but the maximum contribution is 50 %. They note that by varying operational parameters, the production and release of C-14 from PWRs can be decreased. However, pH and electrochemical potential do not significantly affect production and releases from BWRs. Information is not supplied on how these parameters are currently varied in recent or future PWR operations, so the implications for inventory cannot be explored in this review even qualitatively, let alone quantitatively.

It is said that 'in PWRs, a large fraction of the gaseous releases is as hydrocarbons, thus, before being scrubbed by alkali, the hydrocarbons must first be catalytically oxidised to CO_2'. It is added that any C-14 trapped as CO_2 could be precipitated as calcium or barium carbonate, creating a low leach-rate waste form for C-14. This is consistent with assumptions for waste form leachability in Bush *et al.* [1984]. However, it is not made clear if the process discussed is actual or planned practice, so the implications for SFR inventory are not obvious.

EPRI [1995]: Apart from references made above, we note that these authors also refer to use of Co-60 for correlation with C-14, specifically in relation to C-14 in resins. The discussion on chemical form is in agreement with the above commentary, or provides the justification for it. We note that they conclude that chemical form of C-14 in resins and filtration systems should be dealt with specifically, i.e. taking account of reactor and operation specific details. However, they also give details confirming that BWR IEX resins will have much lower C-14 concentrations because the C-14 is driven off in the off gas system when the steam is condensed. This result seems not to be taken account of in SKB's SFR inventory justification. That is, all other things being equal, the BWR contribution seems to be similar to the PWR contribution. However, from the references reviewed, as noted above, we are not able to clearly distinguish the BWR and PWR contributions, since Ringhals 1 and Ringhals 2, 3 and 4 inventory data are all lumped together.

Hesbol *et al.* [1990]: These authors suggest the use of an empirical correlation factor for C-14, but do not suggest a value. This concept seems to have been applied by Lindgren *et al.* [1998], but without the empirical basis being provided. Hesbol *et al.* [1990] suggest that organic carbon is not retained in the IEX system, apparently in disagreement with Lindgren *et al.* [1998] discussing the results of EPRI [1995]. This may be because different types of IEX resin are being considered. The detail has not been extracted in this review and may not actually be available in the references considered.

2.1 Summary on the chemical form of C-14

The following, reproduced with the permission of EPRI, is a summarising table identifying the predominant chemical form of C-14 in different parts of the cycle (from EPRI [1995]):

	PWR	**BWR**
Coolant waters	58–95 % organic	52–87 % inorganic
Modifying operating factors:	– Hydrogen gas over-pressure	– Hydrogen injection
	– Nitrogen addition	
	– Venting operation	
Gaseous releases	80–94 % organic	97 % inorganic
Resin wastes	72–92 % organic	42–100 % inorganic

In the cited work it was assumed that no releases to the water effluent occurred, in other words the resins were able to retain all C-14 in solution. The authors acknowledge that the attachment mode of the mostly organic species of C-14 is unknown, but probably occurs by some type of sorption process rather than by a classical ion exchange mechanism. This view is in contrast with that of Hesbol *et al.* [1990], where it is said that the organic carbons are inert forms and will not be trapped by ion-exchange resins. This discrepancy could be due to the different resins used, but no specific details are given. This might be resolvable if more characterisation data for the resins were to be obtained. In addition, measurements of C-14 in water effluent could be carried out to check the assumption that carbon is quantitatively retained in the resins.

3 Review of additional material

Results of a literature search are reported in Appendix A. However, it is admitted that the results were not very instructive to the objectives of this review. The implication is that such relevant information as may exist is held as confidential.

3.1 Situation in Spain

An investigation has been carried out on how the issue of C-14 in 'spent' ion exchange resins is handled in Spain. The following comments are drawn based on information from ENRESA (the agency for managing the radioactive waste) and CSN (the regulator).

All the low and medium level activity wastes in Spain are disposed of in the El Cabril facility. Producers are required to measure and report Cs-137 and Co-60 in their operative wastes, and then ENRESA assesses the content of a number of other radionuclides, including C-14, using scale factors based on statistical studies. At El Cabril, there is only a limit on the total amount of C-14 to be disposed of, and that limit is 2 TBq. Based on that and the room available in the disposal cells, ENRESA derives limits for acceptance of individual waste packages. No documentation has been obtained giving details of this process.

3.2 Situation in Canada

From the literature review an interesting paper on the management of spent ion exchange resins from CANDU reactors has been found, Miller *et al.* [1997]. The main difference from LWRs is that spent resins are first de-deuterated, but the issue of the disposal remains important. The current practice of Ontario Hydro (now called Ontario Power generation, OPG) is to store the spent IEX resin from the generating stations in liners containing carbon steel containers. This practice is for short term purposes and is not consistent with long term environmental and safety programs. Therefore, safer and more reliable options are being sought for long term spent resin waste management. Major factors in the planning are the potential impact of the C-14 and tritium in about 65 % of the total resin waste (moderator and reactor coolant resins) A number of the options presently being studied, prior to ultimate disposal of this waste are as follows:

1. **Cementation of all resin waste and disposal**
   C-14 has a major impact on processing and disposal plans and it may require disposal of the cementious waste form as intermediate or high-level radioactive waste, as opposed to low-level. (The waste category definitions are specific to Canada.)
2. **Cementation of C-14 bearing resin and volume reduction of balance for disposal**
   This option entails cementation of the high C-14 resins (moderator and reactor coolant resins), while processing the balance (35 %) for volume reduction.
3. **C-14 stripping and disposal of C-14 free resin in high integrity containers**
   At present, there are no fully commercialised processes for C-14 stripping from spent resins, although some processes are being investigated (acid stripping, supercritical CO_2 extraction, cryogenic distillation).

These options are presently under study in Canada bearing in mind technical, financial and regulatory aspects. See also abstract in Appendix A for Jantzen & Peeler [1996], which discusses similar work in progress in the USA.

3.3 Situation in UK

C-14 in Sizewell B PWR operating wastes (from the 1998 United Kingdom Radioactive Waste Inventory, Nirex and DETR, Oct 1999, available as CD.)

Stored quantities for which C-14 inventories are not indicated as zero or trace, as at 1.4.98. The comment with respect to the most significant C-14 waste stream indicates notable uncertainty.

Operational waste stream	Stored quantity (TBq/m^3)	Future arisings (TBq/m^3)	Comments
CVCS resins	5.66E-02	5.66E-02	Best estimate, accurate to a factor of 10.
Spent cartridge filter	1.1E-01	3E-09	Present probably as an oxide. Not significant.
Sludges	N/A	3E-06	Traces as organic salts.
Miscellaneous contaminated equipment and material		1E-05	
Spent resins			Trace present but no quantities given.

3.4 Situation in France

French inventory document [ANDRA, 1998] does not provide details of C-14 in wastes to the level of detail relevant to this revue. However, it is clear from the following that significant consideration has been given to the issue.

3.5 European Commission study

Noe *et al.* [1998], in a study for the European Commission and coordinated by the Commisariat a l'Energie Atomique (CEA), considered analytical techniques for determining waste inventories as well as the identification of possible correlation factors. Measurement methods and results were made and reported for, among other things, a range of LWR operating wastes and radionuclides, including in some cases, C-14.

The authors suggest a correlation based on geometric means of the concentrations of the radionuclides is more appropriate than one based on the arithmetic mean. This is because the measurement results for any particular radionuclide tend to be lognormally distributed. Results are provided for the correlation parameters for C-14 in Belgian PWR wastes, correlated to Co-60, and for C-14 in French PWR wastes, also correlated to Co-60. The quality of the correlation data is indicated as applicable, i.e. useful, based on consideration of the amount of data and other factors. However, no details are provided of the particular waste streams considered. For

German power plants data are provided for PWR wastes (correlated with Co-60 and Cs-137) and BWR wastes (only correlated to Co-60). Again the quality of the information is described as applicable; however, again it is not clear what actual waste streams were analysed. Results for consideration of Spanish power plant wastes, based on comparison with Co-60, suggested no useful correlation. Pooled data for European PWR and BWR wastes suggest a useful set of correlation parameters for PWR waste based on Co-60, but no useful correlation for BWRs.

3.6 More recent EPRI work

A report prepared by EPRI [1999] has been made available for this review. The report notes the significance of chemical form for post disposal releases to the environment but, as regards information on chemical form, confirms the information in EPRI [1995]. In addition, from a mass balance study of wastes sent to the Barnwell facility, they find that 8% of the produced C-14 goes to LLW. This is consistent with data included in the SKB material, as well as the previous EPRI work, which suggested a range from 5–20 %. However, this range is significantly higher than the 1% retention in solid waste assumption made in Lindgren *et al.* [1998], which is then used to justify a correlation coefficient of 1E-3 to Co-60.

4 Conclusions

The following conclusions are drawn tentatively, since the review process may not have been able to access all information available within SKB material and elsewhere. Some of the source material has not been entirely clear to the reviewers and may have been misinterpreted.

A general difficulty arises in that the technical measurements, which can provide good data, are limited to relatively few examples, and the results cannot be readily extrapolated to other circumstances. Sometimes the measurements focus on implications for releases and sometimes for solid waste management, but not usually for both. This means that the full value of the measurements is sometimes missed because the information relevant to interpretation of the results in a wider context, e.g. for solid waste management as well as control of discharges, has not been reported.

Information is not supplied on how these parameters are currently varied in recent or future reactor operations, so the implications for inventory cannot be explored even qualitatively, let alone quantitatively. More broadly, apparent options for controlling C-14 production and distribution among operating effluent and solid wastes are discussed, but it is not made clear whether the processes discussed are actual or planned practice, so the implications for SFR inventory are not obvious.

Chemical form of the C-14 in the waste from BWRs and PWRs

It is clear that chemical form varies between BWR and PWR operating wastes, but that operational factors can also affect the chemical form, especially for the PWR wastes.

It is also clear that chemical form can be an important factor affecting mobility in a repository such as SFR.

However, the information provided for the review does not permit a clear separation of PWR and BWR repository source terms. Furthermore, the work to determine the source term inventory does not appear to take account of the operational factors referred to above. Even if it did, the reviewed documents do not make clear what the operational features were in the past, nor what they will be in the future. Therefore, the significance of these factors for the assumed SFR C-14 inventory and chemical form estimates cannot be clearly addressed.

Production rate of C-14 in BWRs and PWRs and quantification of the source term in the IEX waste

It is clear that inventory estimates for C-14 rely heavily on the use of a correlation factor, a relationship between Co-60 levels in wastes and C-14 levels. This approach is used in other countries and is at least partly justified for PWR wastes in work carried out for the European Commission. Data for correlations relating to BWR wastes appear inadequate to justify their application to inventory assessment, unless the correlations are determined for specific reactors and not on a generic basis.

The choice of correlation used for the SFR inventory assessment seems to be based on an assumed 1 % retention of total C-14 produced in reactors within solid operating wastes. This value seems lower than would be expected according to other sources, which suggest somewhere in the region of 5 to 20 %. However, there may be some misunderstanding about whether the total C-14 produced refers only to coolant C-14 or also to C-14 produced in fuel and cladding. The information supplied does not allow a check of the total C-14 creation and subsequent distribution mass balance.

The distribution of the C-14 in the IEX waste from BWR between the resins used for treatment of the primary cooling water and the resins used for treatment of the condensate water

The source documents reviewed do not allow a clear evaluation of this issue. Among other things, we cannot distinguish between information about how C-14 would behave in particular circumstances and the circumstances actually occurring at the sites producing the waste.

Quantification of the uncertainties

The SFR inventory assessment includes a so-called realistic estimate for C-14 in SFR wastes. The cautious estimate for C-14 inventory appears to be based only on generic waste arisings information, not upon consideration of factors, which could affect production of C-14 or its uptake and retention in wastes going to SFR.

Based on the discussion of arisings and of chemical form, as well as experience in other countries, there appears to be considerable uncertainty in this estimate and in the chemical form that it may be in. An upper limit can reasonably be set based on knowledge of the history of operation of reactors and assumptions about future operation. However, the information available from this review does not allow that upper estimate to be made.

It is suggested here that a useful realistic estimate, and a useful understanding of the important uncertainties, could be made, based on a study of C-14 mass balance in reactor systems. It would be necessary to take account of:

- each reaction type giving rise to generation of C-14 in fuel, cladding and coolant;
- the operating history and planned future of each reactor, including the operational factors which affect C-14 uptake into solid wastes, as well as any information regarding possible release from fuel or fuel cladding into waste streams; and
- the discharge history and planned future of each reactor, with respect to C-14 in atmospheric and liquid discharges.

Such a study would enable the options for managing discharges to air and water, as opposed to uptake into solid wastes and disposal in SFR, to be evaluated. Since the other sources of C-14 are not negligible, account should be taken of these other sources, notably CLAB and Studsvik, in evaluating an appropriate C-14 waste management strategy.

5 References

ANDRA (1998): Inventaires National des Dechets Radioactifs, etabli par l'Observatiore de l'ANDRA. Agence nationale pour la gestion des dechets radioactifs, Chatenay-Malabry.

Bush RP, Smith GM and White IF (1984): Nuclear Science and Technology, Carbon-14 Waste Management, Final Report EUR 8749, Commission of the European Communities, Brussels.

EPRI (1995): Characterisation of Carbon-14 Generated by the Nuclear Power Industry, TR-105715, Project 2724-04, Final Report, EPRI, Palo Alto, California, USA.

EPRI (1999): Carbon-14 in Low Level Waste, TR-107957, Final Report, EPRI, Palo Alto, California, USA.

Hesbol R, Puigdomenech I and Evans S (1990): Source Terms, Isolation and Radiological Consequences of Carbon-14 Waste in the Swedish SFR Repository. Technical Report TR 90-02, SKB, Sweden.

Lindgren M, Pers K, Wiborg M and Brodén K (1998): Low and Intermediate Level Waste in SFL 3-5: Reference Inventory, SKB, Sweden.

Noe M, Muller W, Gens R, Gili M, Morales A, Yates A and Ormai P (1998): Development of Methods to Provide an Inventory of Radiologically Relevant Radionuclides: Analytical Methods and Correlations of Data. European Commission EUR 17978, Luxembourg.

Miller RE, Erdebil I, Solaimani M, Evans DW and Carney M (1997): Life-cycle management of spent ion exchange resins from candu reactors. In: Waste Management 97, March 2–6, 1997, Tucson, AZ, USA.

Riggare P and Johansson C (2001): Project SAFE – Low and Intermediate Level Waste in SFR-1, Draft Report R-01-03 (29 June 2001), SKB, Sweden.

SKB (2001): Final Safety Analysis of SFR Reported by SKB, (Chapter 5.8-5.10) SKB.

Thegerström C and Hård E (1981): Aktivitetsinnehåll i reaktoravfall, SFR 81-08, SKBF/KBS, Studsvik Energiteknik AB, Sweden.

Thierfeldt S and Deckert A (1995): Radionuclides Difficult to Measure in Waste Packages, BS-Nr 9203-6, Final Report, Brenk Systemplanung Aachen, Germany.

Torstenfelt B and Olsen M (1996): SSI P 877.95 Reduction of C-14 Releases from Nuclear Power Plants, SDA 96-1098, ABB, Sweden.

Appendix A

Literature review

A literature search of the IAEA INIS (International Nuclear Information Service) database was conducted. Very few documents relating to carbon-14 reactor operating wastes were found. The key words searched, the number of results found, and any relevant abstracts are listed below.

Search Criteria	Number of results for each CD-Rom (Years)							
	1976–1979	1980–1983	1984–1986	1987–1989	1990–1992	1993–1996	1997–2000	Jan–Sept 2001
C14	17	26	1	16	21	23	39	4
Operating waste	3	6	2	3	4	17	5	1
Reactor operating waste	0	3	1	0	0	0	0	0
C14 inventory	0	0	0	1	0	0	0	0
Inventory		769	733	976	842	1,764	1,435	189
IEX	0	0	0	0	0	2	2	0
Ion exchange resin	147	189	129	132	108	146	148	24
Chemical species	69	120	110	125	126	160	153	30
LWR	1,281	1,390	1,273	1,220	1,006	1,211	871	160
Light water reactor	734	983	876	945	778	852	619	79
PWR	6,695	10,003	9,236	10,359	9,247	10,547	8,713	1,213
Pressurised water reactor	42	70	43	77	55	77	84	18
BWR	4,025	5,588	5,064	5,324	4,569	4,805	3,234	328
Boiling water reactor	545	450	533	571	621	747	481	38

Below is the selection of abstracts from documents listed on the INIS database that appear to be relevant to this project. The heading show the CD year and the keyword criteria used to find the document.

1976–1979, 'C14'

Amlinger H and Lerch G (1977): Quasi-null release of radioactive gases from nuclear power plants achieved by low temperature rectification. Atomkernenergie-Kerntechnik-Germany- F.R. (19143579). v. 33(1), pp. 47–49.

Abstract: The conventional waste gas processing facilities of nuclear power stations cannot ensure complete retention of the activities contained in the waste gas. The residual activity is governed by Kr85 and C14 because of their long half-lives. Waste gas processing facilities with low temperature rectification make it possible to retain both Kr85 and the much smaller quantities of C14 which occurs mainly in the form of CO_2. The CO_2 is frozen out in the process of cooling the waste gas flow down to the rectification temperature, and the krypton is separated out in the rectification column together with xenon.

Bonka H, Bruessermann K, Schwarz G and Willrodt U (1977): Production and emission of carbon-14 from nuclear power stations and reprocessing plants and its radioecological significance. Technische Hochschule Aachen. Proceedings of the 4th International congress of the International Radiation Protection Association. Paris, 24–30 April 1977. v. 3, pp. 945–948.

Abstract: In nuclear power reactors with 1,000 MWe full load capacity C14 will be produced at rates of 10 to 100 Ci/a according to the reactor type. The yearly emission rate for LWR is assessed at 10 Ci, for HTR at 0.1 Ci and for LMFBR at 1 Ci. The corresponding RP for 40,000 MWe installed nuclear reactor capacity may release about 500, 3,000 and 100 Ci/a according to the nitrogen impurities in the fuel elements and the coolant of the reactor type. In view of these assumptions the total body dose of the population in the vicinity of present commercial power reactors in the Federal Republic of Germany is significantly influenced by C-14, although the entire dose itself is very low. Regarding the collective dose to the world population radiocarbon is of the greatest importance for both nuclear power plant emissions and for gaseous wastes from reprocessing plants because of its wide dispersion in the ecosystems. The exposure due to globally distributed C-14 is expected to increase significantly from the year 2000 on. In the long term it is therefore necessary to find a way of lowering the emissions, for example by reduction of the N-impurities, or by collection of radiocarbon with krypton control systems in RP, or by changing the head-end process of HTR-RP.

1976–1979, 'Operating waste'

Marcus FR (1977): Industrial aspects of radioactive waste management in Western Europe. Nordic Co-ordination Committee for Atomic Energy, Risoe, Denmark; International Atomic Energy Agency, Vienna (Austria). Nuclear power and its fuel cycle. Proceedings of an international conference held by the IAEA in Salzburg, 2–13 May 1977. Vienna. IAEA. 1977. v. 4, pp. 369–379. Vol. 4 is entitled 'Radioactivity management'.

Abstract: In 1980 about 120 nuclear power reactors with 70,000MW(e) will be in operation in Western Europe, and this number will be doubled by the second half of the 1980s, when the nuclear capacity in operation is expected to be 180,000MW(e). Predictions are made of the waste management requirements resulting from this nuclear expansion. Until a few years ago nuclear research and the use of isotopes in medicine have been the dominating source of radioactive waste. Now there is a much larger proportion from the day-to-day operation of nuclear power reactors. The amount of waste from reprocessing spent reactor fuel will rise more slowly. Waste production in other fuel cycle industries is relatively insignificant. Approximately 30 reactors and other nuclear plants will be taken out of operation in Western Europe by about 1990. The large-scale handling of these wastes calls for overall management schemes based on clear policies for storage and disposal. Questions are identified which will have to be answered within the next few years in order to allow the orderly development of such large-scale waste management. These questions deal with (i) rules and regulations, (ii) new technical evidence, (iii) administrative framework and responsibilities. Several areas of waste management are well suited to commercial waste operating firms already established in a number of European countries. The scope for waste operators may include transport of waste, operation of own or government-owned treatment and storage installations, and disposal operations. Development requirements originally suggested by the Foratom waste study group are discussed in the light of the latest developments as seen by European industry.

1980–1983, 'Reactor operating wastes'

Carter TJ (1982): Radioactive waste management practices at a large Canadian electrical utility. Radioactive-Waste-Management-Oak-Ridge, Tennessee-USA. (Jun 1982). v. 2(4), pp. 381–412.

Abstract: Ontario Hydro is a large publicly owned electric utility in Canada serving approximately 8 million customers in the Province of Ontario. It has over 24,000 MWe of installed

generating capacity split between hydraulic, fossil fuels and CANDU nuclear generating stations. It is estimated that by 1991 Ontario Hydro will have 13,500 MWe of CANDU generation. The author describes Ontario Hydro's liquid and gaseous emission control systems and performance; the solid reactor operating waste systems and experience; and briefly describes the common Atomic Energy of Canada Ltd. (AECL/CRNL) and Ontario Hydro project for the long term isolation of reactor operating and maintenance wastes.

Haug HO (1981): Decay calculations on medium-level and actinide-containing wastes from the LWR fuel cycle. Pt. 1. Basic data evaluation including activity and thermal decay power. Inst. fuer Heisse Chemie. Kernforschungszentrum Karlsruhe G.m.b.H. (Germany, F.R.). Projekt Wiederaufarbeitung und Abfallbehandlung. Oct 1981. 72 p.

Abstract: A number of basic data on medium-level and actinide-containing waste streams from the LWR fuel cycle were evaluated and the activity and thermal decay power were calculated for the nuclide inventories of cladding hulls and fuel assembly structural materials, for feed clarification sludge, medium-level aqueous process waste, low-level solid transuranium waste and for medium-level reactor operating waste. The activity as a function of decay time of the medium-level wastes decreases within 500 to 600 years by 1 to 3 orders of magnitude and is at the same time about 1 to 2 orders of magnitude lower than the activity of the high-level waste. The thermal decay power of the medium-level wastes decreases after 10 to 100 years by about 3 orders of magnitude and is about a factor of 10 to 100 less than that of high-level waste. In the very long term the residual activity (and thermal power) decreases only slowly due to the long half lives of the dominant actinides. The activity after more that 1,000 years is about 1 to 2 orders of magnitude lower than that of high-level waste, the low-level transuranium waste by a factor 10 to 4, respectively. The activity per unit volume of the packaged waste of the medium-level and actinide-containing wastes because of the bigger volume of the conditioned wastes is lower by 2 to 4 orders of magnitude up to about 500 years. After more than 1,000 years the activities per unit volume are lower by a factor of 20 to 200 than that of high-level waste.

1980–1983, 'C14'

SKB (1982): SKB annual report 1981. Including summaries of technical reports issued during 1981. Svensk Kärnbränsleförsörjning AB, Stockholm. SO: May 1982. 133 p. SKBF-KBS-TR--81-17 (SKBFKBSTR8117).

Abstract: The nuclear power utilities have commissioned the jointly owned Swedish Nuclear Fuel Supply Company (SKBF) to assume responsibility for a safe handling of the waste and a safe final storage. KBS is the department within SKBF that is responsible for research and development within the area of radioactive waste management. The government agency of PRAV (the National Council for Radioactive Waste) was dissolved as of mid-year 1981 and its research activities were transferred to SKBF/KBS. Simultaneously, the National Board for Spent Nuclear Fuel, NAK, was created and charged with the duties of overseeing the work being conducted by SKBF within the nuclear waste field and administering the funds that are to be set up for the financing of future waste management activities. The present annual report describes activities within KBS during 1981. The work conducted during the year has been concentrated on three areas: 1) A systematic review has begun of geologically interesting areas in Sweden that might be suitable as sites for a final repository for high level waste or spent fuel. 10–20 areas are scheduled for study during the 1980s. 2) The chemical research has been broadened in order to future understanding of the chemical interplay that exists in the repository between the canister material, the buffer, the waste matrix and the groundwater. The retardation effects associated with the transport of radioactive elements with the groundwater in the bedrock also constitute an important subject of these studies. 3) The preliminary planning and engineering of a final repository for low- and medium-level operating waste from the Swedish reactors is in progress. The aim is to submit an application during the spring of 1982 for permission to build the facility at the Forsmark Nuclear Power Station.

Bundesministerium des Innern (1980): Status report on radionuclide transfer. Statusbericht ueber den Transfer von Radionukliden. Bundesministerium des Innern, Bonn (Germany), p. 166.

Abstract: At the suggestion of the Federal Ministry of the Interior, in June 1978, a group of scientists from several institutions who are active in the field of radionuclide transfer or are interested in these problems got together. During the discussions of the work team, especially the transfer soil/plants was emphasised. Then the work team set up a status report on the transfer of the radionuclides relevant in the sense of the radiation protection act. The nuclides H3 and C14, the isotopes of the Sr, J, and Cs, Tc99, the so-called corrosion nuclides Mn54, Fe59, co-isotopes and Zn65, and isotopes of Pu, Am, and Cm were regarded as important for a possible radiation exposition. Recent investigations revealed that also the natural radionuclides Ra226, Po210, and Pb210 should be covered by the investigations. The goal of this status report is to present the level of knowledge on the transfer of these radionuclides to man in a brief form, giving hints at the most important literature. It was requested by the Federal Ministry of the Interior, as far as possible, to indicate transfer factors which are necessary for the radioecology act to be decreed according to Para. 45 of the radiation protection act. Another goal of the report was to show the gap in the knowledge on the radionuclide transfer. This was thought to help to create a basis for the decisions of the Federal Ministry concerning the support of other investigation projects in the field of transfer of radionuclides.

Bonka H (1980): Environmental radiation exposure due to exhaust air of the reprocessing plant. Radiologische Umgebungsbelastung durch die Abluft der Wiederaufarbeitungsanlage. Technische Hochschule Aachen (Germany). Lehrstuhl fuer Reaktortechnik Atomkernenergie-Kerntechnik-Germany, F.R., v. 32(2), pp. 134 – 141.

Abstract: Nowadays the emissions of radioactive material in nuclear facilities are so low that the radiological impact on the population compared to the effect of the natural radiation exposure is negligibly low. For the planned reprocessing plant for higher emissions have to be taken into account. Due to the increase of the emission height of 100 to 200 m it becomes possible to lower the individual doses so far using conventional retention techniques that the data remain under the limits given by the radiation protection ordinance. The collective doses, however, do not change by this. Due to cost-benefit analysis and taking into account the expected doses in the future due to globally distributed long-lived radionuclides, H3 should be retained to 80–90 %, C14 to approx. 90 %, Kr 85 to approx. 95 % and J129 to approx. 99,5 % in the planned large reprocessing plant.

1984–1986, 'Operating wastes'

Fitzpatrick J, Johnstone AJ and Buchheim B (1985): A comparative assessment of potential waste management procedures for reactor wastes. Radioactive waste management conference. London (UK). 27–29 Nov 1984. Radioactive waste management Proceedings. British Nuclear Energy Society, London, 27–29 November 1984. British Nuclear Energy Society, 331, pp. 277–279.

Abstract: In developing a strategy to manage radioactive wastes in the UK, the Department of the Environment are looking at numerous waste management procedures on an individual waste stream basis. Each of these procedures consists of up to nine elements ranging from waste arising to final disposal. These elements can be grouped under the four headings; treatment and packaging, transport, storage and disposal. In this paper work carried out on behalf of the Department on the assessment of treatment and packaging elements for reactor operating waste streams is reported. The various options feasible for the six elements covering treatment and packaging are addressed and the overall comparison between different waste management procedures described.

1984–86, 'Operating wastes'

Barainca MJ, Coleman JA and Chee TC (1984): Directions and objectives of the Sixth Annual Department of Energy Low-Level Waste Management Program. Annual Low-Level Waste Management Program participants' information meeting. Denver, CO (USA). 11–13 Sep 1984. Oak Ridge National Lab., TN (USA).

Abstract: This paper presents specific concerns for the waste generators and disposal site operators to consider in the course of the meeting. The annual Low-Level Waste Management Program Participants' Meeting is one of several mechanisms used to provide input for the Program's deliberation. Based on the discussions that take place at this meeting and information gained from the Ad Hoc Waste Operating Contractors Committee, Program Review Committee, other agencies, and visits to the Department's facilities, progress can be determined and future needs can be incorporated into the plans. Critical to the achievement of each Program objective is the application of technology that has been developed. Program emphasis is shifting from the development of new technology to large scale in-field demonstrations to validate the improved technologies and maximize their utility. Stabilization techniques, improved trench caps, and improved treatment systems resulting in more stable waste forms are a few examples of these technologies. On the institutional side, states are moving slower to implement their responsibilities under the PL-96-573 for establishing new disposal capacity for low-level waste. Assuming that states continue along the path of establishing new disposal sites, less financial support by the Department will be required in the institutional area. Accordingly, the Department plans to limit its assistance to those tangible activities that contribute toward the management of a stable LLW system over the next two to three years. Discussions during this meeting should focus on what specific activities are required for the establishment of new low-level waste disposal facilities and how the on-going technology activities are meeting the needs of the users.

1987–1989, 'C14 inventory'

Bleier A, Beuerle M, Ellinger M, and Bohlen D (1988): Investigations into the chemical status of C14 after leaching of cladding material from spent PWR and BWR fuel rods in a salt solution. Final report. Siemens AG Unternehmensbereich KWU, Erlangen Germany Bundesministerium fuer Forschung und Technologie, Bonn, Germany Apr 1988. 65 p.

Abstract: Following analysis of its C14 inventory, cladding material from spent PWR and BWR fuel rods was exposed to a saturated NaCl solution for 3 months at 200 sup 0 C in order to gain basic data on C14 behaviour after water ingress into a sealed repository. Cladding corrosion was initiated only after 100 ppm fluoride was added to the leaching medium. The C14 results obtained under these conditions indicate that cladding corrosion mobilizes about 50 % of the C14 in PWR hulls and about 90 % of the C14 in BWR hulls. The mobilized C14 is found 95 % in the 14 CO/ 14 CH4 fraction, whereas 14 CO_2 at 5 % represents a minority. Dissolving hulls in diluted hydrofluoric acid shows similar C14 species distribution. Because on the one hand the corrosion mechanism is not clear and on the other hand the fluoride in salt formations can be made inactive by other salt impurities or by the presence of concrete, further investigations into Zircaloy cladding corrosion are recommended.

1987–89, 'C14'

Czapiewski W, Kreymborg A, Muenster M, and Pink P (1984): Systems study 'Alternative Entsorgung'. 2. part of final report. Technical Annex 18, Calculation of environmental effects of nuclear fuel disposal devices. Gesellschaft fuer Umweltueberwachung m.b.H., Aldenhoven Germany, Kernforschungszentrum Karlsruhe G.m.b.H. Germany, Oct 1984. 89 p.

Abstract: The collective dose due to normal operation of a reprocessing plant is considerably above the expected value of the collective dose in consequence of examined accidents in the reprocessing plant and in the model final stores. For 'integrated fuel disposal', the fuel circuit

causes a collective dose, which is of the same order of magnitude as that of a nuclear power station. The collective dose of the fuel circuit (without a nuclear power station) is caused almost exclusively by normal operation of the reprocessing plant. The collective dose of the reprocessing plant is determined by gaseous radioactivity, where about 50 % of the collective dose up to 1500 km originates from individual doses in the range between 10E5 and 10E7 Sv (1 mrem and 0.01 mrem). Retention of C14 and Kr 85 to 90 % would reduce the collective dose in the reprocessing plant 700 by about 50 %. For 'other fuel disposal techniques', the collective dose of the fuel circuit is about an order of magnitude lower than that of the nuclear power station. The collective dose of the fuel circuit without a nuclear power station up to 1500 km is practically exclusively determined by uranium ore mining, where individual doses below 10E7 Sv (0.01 mrem) contribute quite considerably.

1993–1996, 'IEX'

Jantzen CM, Peeler DK and Cicero CA (1995): Vitrification of ion-exchange (IEX) resins: Advantages and technical challenges. Annual meeting and exposition of the American Ceramic Society (ACerS). Indianapolis, IN (United States). 24–28 Apr 1995.

Abstract: Technologies are being developed by the US Department of Energy's (DOE) Savannah River Site (SRS) in conjunction with the Electric Power Research Institute (EPRI) and the commercial sector to convert low-level radioactive ion exchange (IEX) resin wastes from the nuclear utilities to solid stabilized waste forms for permanent disposal. One of the alternative waste stabilization technologies is vitrification of the resin into glass. Wastes can be vitrified at elevated temperatures by thermal treatment. One alternative thermal treatment is conventional Joule heated melting. Vitrification of wastes into glass is an attractive option because it atomistically bonds both hazardous and radioactive species in the glass structure, and volume reduces the wastes by 70-80 %. The large volume reductions allow for large associated savings in disposal and/or long term storage costs.

1993–1996, 'Operating wastes'

Bucher T (1996): ISRA, the Swiss information system for radioactive wastes as part of quality assurance measures. Management of radioactive wastes from nuclear power plants. Brugg-Windisch (Switzerland). 27–29 Mar 1996. Bewirtschaftung radioaktiver Betriebsabfaelle aus Kernkraftwerken. SVA-Deepening course: management of radioactive wastes from nuclear power plants. Proceedings, SVA, 400 p.

Abstract: In the management of radioactive operating waste, a complete documentation must be kept of the required quality assurance measures which ensure that the specified requirements are adhered to. Because of the quantity of data and the information requirements of the authorities involved, a Swiss information system for radioactive waste (ISRA) was set up as an EDP documentation system which takes the following tasks into account: – characterisation of the waste binding types, – creation of the individual binding documentation, – bookkeeping and reporting, – storage management and transport. Thanks to ISRA, the documentation in the administration of radioactive waste can be dealt with simply, safely, and economically.

Olin M (1994): Validation of a numerical release model (REPCOM) for the Finnish operating waste disposal systems. Part VI: Intermediate results from the laboratory measurements 1986–1993. Nuclear Waste Commission of Finnish Power Companies, Helsinki (Finland), 1994, 38 p.

Abstract: In Finland the operating waste from four nuclear power plant units will be disposed of in two repositories to be built in the granitic bedrock at the two power plant sites. The aim of this work is to model experimentally the inner structures and materials of the reactor waste repositories and to use the results for the validation of a numerical near field release model, REPCOM. The laboratory arrangements included the following test materials: bitumenized and cemented ion-exchange resin, concrete, crushed rock, and water corresponding to materials in

the existing and planned disposal systems. 137Cs, 60Co, 85Sr, and 90Sr were used as tracers, with which the ion-exchange resin, water or crushed rock was labelled depending on the specimen type.

1997–2000, 'Ion exchange resin'

Jantzen CM (2000): Savannah River Site waste vitrification projects initiated throughout the United States: Disposal and recycle options. Celebrating 50 Years of Excellence in Science Aiken, US Department of Energy (United States). 17 May 2000.

Abstract: A vitrification process was developed and successfully implemented by the US Department of Energy's (DOE) Savannah River Site (SRS) and at the West Valley Nuclear Services (WVNS) to convert high-level liquid nuclear wastes (HLLW) to a solid borosilicate glass for safe long term geologic disposal. Over the last decade, SRS has successfully completed two additional vitrification projects to safely dispose of mixed low level wastes (MLLW) (radioactive and hazardous) at the SRS and at the Oak Ridge Reservation (ORR). The SRS, in conjunction with other laboratories, has also demonstrated that vitrification can be used to dispose of a wide variety of MLLW and low-level wastes (LLW) at the SRS, at ORR, at the Los Alamos National Laboratory (LANL), at Rocky Flats (RF), at the Fernald Environmental Management Project (FEMP), and at the Hanford Waste Vitrification Project (HWVP). The SRS, in conjunction with the Electric Power Research Institute and the National Atomic Energy Commission of Argentina (CNEA), have demonstrated that vitrification can also be used to safely dispose of ion-exchange (IEX) resins and sludges from commercial nuclear reactors. In addition, the SRS has successfully demonstrated that numerous wastes declared hazardous by the US Environmental Protection Agency (EPA) can be vitrified, e.g. mining industry wastes, contaminated harbor sludges, asbestos containing material (ACM), Pb-paint on army tanks and bridges. Once these EPA hazardous wastes are vitrified, the waste glass is rendered non-hazardous allowing these materials to be recycled as glassphalt (glass impregnated asphalt for roads and runways), roofing shingles, glasscrete (glass used as aggregate in concrete), or other uses. Glass is also being used as a medium to transport SRS americium (Am) and curium (Cm) to the Oak Ridge Reservation (ORR) for recycle in the ORR medical source program and use in smoke detectors at an estimated value of $1.5 billion to the general public.

Jantzen CM and Peeler DK (1996): Vitrification of Ion-Exchange (IEX) resins: Advantages and technical challenges. Annual meeting of the American Ceramic Society. Indianapolis, IN (United States). 14–17 Apr 1996. Jain & Peller (eds.). Ceramic transactions: Environmental issues and waste management technologies in the ceramic and nuclear industries II. Volume 72. Westerville, OH (United States). American Ceramic Society. 1996, 539, pp. 113–122.

Abstract: Technologies are being developed by the US Department of Energy's (DOE) Savannah River Site (SRS) in conjunction with the Electric Power Research Institute (EPRI) and the commercial sector to convert low-level radioactive ion exchange (IEX) resin wastes from the nuclear utilities to solid stabilized waste forms for permanent disposal. One of the alternative waste stabilization technologies is vitrification of the resin into glass via conventional Joule heated melting. Vitrification of wastes into glass is an attractive option because it atomistically bonds both hazardous and radioactive species in the glass structure, and volume reduces the waste by 70–80 %. The large volume reductions allow for large associated savings in disposal and/or long term storage costs. This paper evaluates both the advantages of vitrification as a stabilization option for IEX resins and the associated technical challenges of thermally treating organic-based resins.

1997–2000, 'C14'

Lockheed Martin Astronautics (1995): Intelligent Mobile Sensor System for drum inspection and monitoring, Volume 2. Final report, October 1, 1993, April 22, 1995, USDOE Assistant Secretary for Fossil Energy, Washington, DC (United States), 60 p.

Abstract: The objective of the Intelligent Mobile Sensor System (IMSS) project was to develop an operational system for monitoring and inspection activities for waste storage facility operations at several DOE sites. Specifically, the product of this effort was a robotic device with enhanced intelligence and manoeuverability capable of conducting routine inspection of stored waste drums. The system has an integrated sensor suite for problem-drum detection, and creates and maintains a site database both for inspection planning and for data correlation, updating, and report generation. The system is capable of departing on an assigned mission, collecting required data, recording which portions of its mission had to be aborted or modified due to environmental constraints, and reporting back when the mission is complete. Successful identification of more than 96 % of drum defects has been demonstrated in a high fidelity waste storage facility mockup. Identified anomalies included rust spots, rust streaks, areas of corrosion, dents, and tilted drums. All drums were positively identified and correlated with the site database. This development effort was separated into three phases of which phase three is now complete. The first phase demonstrated an integrated system (maturity level IVa) for monitoring and inspection activities for waste storage facility operations. The second phase demonstrated a prototype system appropriate for operational use in an actual storage facility. The prototype employed an integrated design that considered operational requirements, hardware costs, maintenance, safety, and robustness. The final phase has demonstrated the commercial viability of the vehicle in operating waste storage facilities at Fernald, Ohio and the Idaho National Engineering Laboratory (INEL). This report summarizes the system upgrades performed in phase 3 and the evaluation of the IMSS Phase 3 system and vehicle.

2001 Jan–Sept, 'Operating waste'

Kumar S, Ali SS, Chander M, Bansal NK and Balu K (2001): Integrated radioactive waste management from NPP, research reactor and back end of nuclear fuel cycle – an Indian experience. International symposium on technologies for the management of radioactive waste from nuclear power plants and back end nuclear fuel cycle activities, Taejon, Korea, 30 Aug–3 Sep 1999, Technologies for the management of radioactive waste from nuclear power plants and back end nuclear fuel cycle activities. Proceedings Feb 2001, 627 p. IAEA, International Union of Producers and Distributors of Electrical Energy, Brussels (Belgium), Nuclear Energy Institute, Washington DC (United States); OECD Nuclear Energy Agency, Paris (France).

Abstract: India is one of the developing countries operating waste management facilities for entire nuclear fuel cycle for the last three decades. Over the years, the low and intermediate level (LIL) liquid waste streams arising from reactors and fuel reprocessing facilities have been well characterised and different processes for treatment, conditioning and disposal are being practised. LIL waste generated in nuclear facilities is treated by chemical treatment processes where majority of the activity is retained in the form of sludge. Decontamination factors ranging from 10 to 1000 are achieved depending upon the process employed and characteristics of the waste. At an inland PHWR site at Rajasthan, the LIL waste is concentrated by solar evaporation. To augment the treatment capability, a plant is being set up at Trombay to treat LIL waste based on reverse osmosis process. Alkaline waste of intermediate level activity is being treated by using indigenously developed resorcinol formaldehyde resin. Solid radioactive waste is volume reduced by compacting, baling and incineration depending on the nature of the waste. Cement matrix is employed for immobilisation of process concentrate such as chemical sludge, ash from incinerators etc. The solid waste, depending on the activity contents, is disposed in underground engineered trenches in near surface disposal facility. Bore well samples around the trench are drawn periodically to ascertain the effectiveness of the disposal system. The gaseous waste is treated at the source itself. High efficiency particulate air (HEPA) filter and impregnated activated carbon is employed to restrict the release of airborne activity to the environment. Radioactive waste discharges are kept well below the authorised limits prescribed

by the regulatory authorities. This paper covers the waste management practices being adopted in India for treatment, conditioning, interim storage and disposal of low and intermediate level waste arising from the operation of nuclear power plant, research reactor and fuel reprocessing facilities.

2001 Jan–Sept, 'C14'

Dubourg M (2000): Radiological impact of the carbon 14 in the decommissioning of gas cooled reactors, Safewaste 2000 -2. International Conference, Nuclear Waste: From Research to Industrial Maturity, Montpellier (France) 2–4 Oct 2000, Societe Francaise d'Energie Nucleaire Paris (France 2000 (v.1–2), 888, pp. 847–855.

Abstract: Carbon-14 is a weak beta emitter (maximum energy 0.156 Mev) and it has a long half life (5,730 years). Is produced continuously in the atmosphere at a rate of 27,000 Ci/year or one peta-becquerel per year by action of cosmic rays on the nitrogen of the atmosphere. The inventory in the atmosphere was temporarily increased and has more than doubled by atmospheric nuclear weapons tests in the 1950's and 1960's. It has been recognised in the past decade that substantial amount of carbon-14 are produced in nuclear power reactors. Because of its long half life and because it is readily incorporated into biological systems by complex mechanisms of the carbon cycle, carbon-14 could have a significant radiological impact. The carbon 14 emission from the operating reactors has to be carefully assessed, because the carbon 14 releases into organic form or CO sub 2 form have a major radiological impact on the critical group of population around nuclear installations. The purpose of this paper is to review the main sources of carbon-14 releases and to evaluate the radiological impact mainly in the case of Gas Cooled Graphite reactors decommissioning strategies and waste treatment of graphite moderators including graphite incineration. The radiological impact of an incinerator able to treat 600 tons of French graphite per year, shows that gaseous releases remain acceptable for the most exposed group according to ICRP (International Commission on Radiological Protection) criteria; and in any case, it is much lower than the limit of 1 mSv/year established for the general public (ICRP 60) being in fact 4 % of the allowable limit. However innovative technologies could be applied to off-gas treatment in order to reduce significantly the release of C14 into the environment, by static centrifugation and separation of the C14 O sub 2 from the remaining off-gas streams and to stabilize the C14 into solid form such as the insoluble barium carbonate, while a significant waste volume reduction of graphite could be achieved after incineration (over 90 % of volume reduction), which represents a significant advantage for deep geological repository for the storage of radwaste containing long half-life radionuclides such as C14.

SSI-rapporter 2002

SSI reports 2002

2002:01 SAR och utstrålad effekt för 21 mobiltelefoner
Avdelning för miljöövervakning och mätberedskap.
Gert Anger 120 SEK

2002:02 Natural elemental concentrations and fluxes: their use as indicators of repository safety
SKI-rapport 01:51

2002:03 SSI:s granskning av SKB:s FUD-program 2001
Avddelningen för avfall och miljö.
Björn Hedberg, Carl-Magnus Larsson, Anders Wiebert, Björn Dverstorp, Mikael Jensen, Maria Norden, Tomas Löfgren, Erica Brewitz, John-Christer Lindhé och Åsa Pensjö.

2002:04 SSI's review of SKB´s complement of the RD&D programme 1998
Avdelningen för avfall och miljö.
Mikael Jensen, Carl-Magnus Larsson, Anders Wiebert, Tomas Löfgren and Björn Hedberg.

2002:05 Patientdoser från röntgenundersökningar i Sverige – uppföljning av åtgärder
Avdelningen för personal- och patientstrålskydd.
Helene Jönsson och Wolfram Leitz. 60 SEK

2002:06 Strålskyddskonsekvenser vid villaeldning med ^{137}Cs-kontaminerad ved
Avdelning för miljöövervakning och mätberedskap.
Hans Möre och Lynn Hubbard 60 SEK

2002:07 Säkerhets- och strålskyddsläget vid de svenska kärnkraftverken 2001

2002:08 Mammography – recent technical developments and their clinical potential
Avdelningen för personal- och patientstrålskydd.
Bengt Hemdal, Ingvar Andersson, Anne Thilander Klang, Gert Bengtsson, Wolfram Leitz, Nils Bjurstam, Olof Jarlman and Sören Mattsson 80 SEK

2002:09 Personalstrålskydd inom kärnkraftindustrin under 2001
Avdelningen för personal- och patientstrålskydd.
Ansi Gerhardsson, Thommy Godås, Peter Hofvander, Ingemar Lund, Lars Malmqvist, Hanna Ölander Gür 70 SEK

2002:10 Radonåtgärders beständighet
Avdelningen för miljöövervakning och mätberedskap.
Bertil Clavensjö 120 SEK

2002:11 National plan for achieving the objectives of the OSPAR strategy with regard to radioactive substances
Avdelningen för avfall och miljö. 60 SEK

2002:12 Formulation and presentation of risk assessments to address risk targets for radioactive waste disposal
SKI-rapport nr 02-21

2002:13 SSI's review of SKB's RD&D programme 2001
Avdelningen för avfall och miljö.

2002:14 Review of C-14 inventory for the SFR facility
Graham Smith, Joan Merino and Emma Kerrigan
Avdelningen för avfall och miljö. 60 SEK

SSI Rapport

STATENS STRÅLSKYDDSINSTITUT, SSI, är central tillsynsmyndighet på strålskyddsområdet. Myndighetens verksamhetsidé är att verka för ett gott strålskydd för människor och miljö nu och i framtiden.

SSI är ansvarig myndighet för det av riksdagen beslutade miljömålet *Säker strålmiljö*.

SSI sätter gränser för stråldoser till allmänheten och för dem som arbetar med strålning, utfärdar föreskrifter och kontrollerar att de efterlevs. Myndigheten inspekterar, informerar, utbildar och ger råd för att öka kunskaperna om strålning. SSI bedriver också egen forskning och stöder forskning vid universitet och högskolor.

SSI håller beredskap dygnet runt mot olyckor med strålning. En tidig varning om olyckor fås genom svenska och utländska mätstationer och genom internationella varnings- och informationssystem.

SSI medverkar i det internationella strålskyddssamarbetet och bidrar därigenom till förbättringar av strålskyddet i främst Baltikum och Ryssland.

Myndigheten har idag ca 110 anställda och är beläget i Stockholm.

THE SWEDISH RADIATION PROTECTION AUTHORITY (SSI) is the government regulatory authority for radiation protection. Its task is to secure good radiation protection for people and the environment both today and in the future.

The Swedish parliament has appointed SSI to be in charge of the implementation of its environmental quality objective *Säker strålmiljö* ("A Safe Radiation Environment").

SSI sets radiation dose limits for the public and for workers exposed to radiation and regulates many other matters dealing with radiation. Compliance with the regulations is ensured through inspections.

SSI also provides information, education, and advice, carries out its own research and administers external research projects.

SSI maintains an around-the-clock preparedness for radiation accidents. Early warning is provided by Swedish and foreign monitoring stations and by international alarm and information systems.

The Authority collaborates with many national and international radiation protection endeavours. It actively supports the on-going improvements of radiation protection in Estonia, Latvia, Lithuania, and Russia.

SSI has about 110 employees and is located in Stockholm.

Statens strålskyddsinstitut
Swedish Radiation Protection Authority

Adress: Statens strålskyddsinstitut; S-17116 Stockholm;
Besöksadress: Karolinska sjukhusets område, Hus Z 5.
Telefon: 08-729 71 00, Fax: 08-729 71 08
Address: Swedish Radiation Protection Authority;
SE-17116 Stockholm; Sweden
Telephone: + 46 8-729 71 00, Fax: + 46 8-729 71 08
www.ssi.se