Kristallin-I

Conclusions from the regional investigation programme for siting a HLW repository in the crystalline basement of Northern Switzerland

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FOREWORD

This report provides an overview of the results obtained during the regional (Phase I) investigation of the crystalline basement of Northern Switzerland as a potential host rock for a repository for high-level and long-lived intermediate-level radioactive wastes. This overview is supported by a detailed synthesis of the geological information obtained during this 10-year study (THURY et al. 1994) and a performance assessment which places the geological data in the context of repository safety (NAGRA 1994). The repository concept previously presented in Project Gewähr 1985 (NAGRA 1985) is reassessed, the requirements for future investigations to determine siting suitability in a specific area are identified and the field work required to characterise an identified site is outlined.

This project has involved large numbers of Nagra staff and external contractors. Its integration was carried out by a Project Team including, in particular,

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with a coordinating Core Group including

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Overall responsibility for the high-level waste programme lies with C. McCombie; Kristallin-I was coordinated by I. McKinley.
SUMMARY

The current Nagra strategy envisages disposal of high-level and long-lived, intermediate-level radioactive waste in a deep geological repository. The crystalline basement of Northern Switzerland was identified as a potential host rock for such a repository and a three-phase geological characterisation plan was defined and initiated in 1981. Kristallin-I involves a synthesis of the results from the recently completed Phase I (regional scale) field investigations. This synthesis is very much based on the repository concept presented in Project Gewähr 1985 (PG’85; NAGRA 1985). PG’85 was judged by the Swiss authorities in 1988 to have demonstrated the basic feasibility of construction of such a repository and showed that the concept introduced for the disposal of vitrified high-level waste (HLW) could provide sufficient assurance of safety. The geological database available at that time was relatively limited, however, and the authorities set requirements for demonstrating more convincingly the availability of suitable siting possibilities in Switzerland (Standortnachweis). Work since 1988 has also been carried out in sedimentary formations, in parallel to the crystalline host rock project documented here.

The main aims of Kristallin-I are:

- Updating and supplementing the PG’85 studies, with particular emphasis on the expanded geological database now available and progress made in understanding mechanisms and processes relevant for performance assessment.

- Documenting completion of Phase I and integrating results in order to provide the basis for selection of potential areas for a siting demonstration project.

- Providing updated technical input for waste management planning and setting future research priorities.

This report provides a concise overview of the entire project. It is supported by two technical synthesis reports, one of which integrates the results of the geological studies (THURY et al. 1994) while the other documents the associated repository performance assessment (NAGRA 1994). These synthesis reports are, in turn, supported by large numbers of more specialist publications, many of which have been released in the Nagra Technical Report (NTB) series.

Selection of the crystalline basement of Northern Switzerland as a potential host rock was based on criteria including good long-term predictability of behaviour, potentially suitable hydrogeological characteristics, low seismicity, absence of exploitable natural resources and favourable rock mechanical/engineering properties. Regional characterisation during Phase I involved extensive seismic surveys and drilling 7 deep (1300-2500m) boreholes, which were analysed in detail. Geological mapping and hydrogeological/hydrochemical surveys were carried out in the research region and in the nearby Southern Black Forest where the crystalline basement outcrops.
Progress since PG'85 is particularly evident in the development of the geological understanding of the basement in the areas of interest and the representation of this understanding in a geo-database for performance assessment. In particular:

- A much improved tectonic model of the region has been developed allowing two potential siting sub-regions (Areas West and East) to be delineated and the understanding of the distribution of major faults within these areas to be formalised in a statistical model.

- A new suite of hydrogeological models has been developed based on a synthesis of more extensive hydraulic measurements. They also directly consider the structural model developed and are constrained by regional geochemical and isotopic measurements.

- Great effort has gone into detailed characterisation of all water-conducting features observed in the deep boreholes and the resulting information has been synthesised into model representations of three classes of such features. These descriptions are supported by new literature studies to define the important sorption and matrix diffusion properties of these water-conducting features.

- Hydrochemical and isotopic data have been synthesised on a regional basis to provide a reasonably consistent picture of groundwater evolution due to rock/water interaction. This not only shows general groundwater flow patterns in the basement but also forms the basis for the definition of reference waters for the two potential siting sub-regions.

- Analysis of possible long-term geological evolution has underpinned the two bounding scenarios presented in PG'85 - particularly with regard to the quantification of expected uplift, erosion and movement along various sizes of faults in the areas of interest over time periods of up to a million years in the future.

In addition, the geosynthesis report provides an integration of all the key information produced to date which, taken as a whole, enhances confidence in the concepts developed in the various sub-disciplines (tectonics, hydrogeology, geochemistry, etc.).

Based on the expected geological structure, a conceptual repository layout has been defined in which "panels" of HLW emplacement tunnels are set out in low-permeability basement between sub-vertical, regional faults. For example, for the reference waste inventory (resulting from a planned 40-year lifetime of the existing 3 GW(e) of installed nuclear power plants), 3 panels in blocks with areas of ~0.3 km² would be sufficient. At a reference depth of about 1000 m below surface, emplacement tunnels would be overlain by at least 100 m of low-permeability host-rock, several hundred metres of higher permeability basement and hundreds of metres of sediments. The repository layout also includes silos for disposal of long-lived intermediate-level waste, but this has not been further analysed within Kristallin-I.
Alternative nuclear power production scenarios and the option of direct disposal of future arisings of spent fuel are considered in Swiss waste management strategic planning but these options are also not discussed in any detail in the Kristallin-I synthesis.

As presented in PG’85, vitrified HLW in a stainless steel fabrication container would be encapsulated in a massive steel canister, which is emplaced horizontally in tunnels backfilled with highly compacted bentonite. The methodology and databases used for assessing the performance of this disposal concept have been developed somewhat since PG’85 with:

- Adoption of a rigorous scenario development and analysis methodology which documents system understanding in a more complete and traceable manner and allows the numerous calculations performed to be structured in a more logical manner.
- Improvement in conceptual model development to better represent the systems studied - particularly for the structure of the water-conducting features in the host rock which provides a basis for modelling radionuclide transport through the host rock.
- Extension of the capabilities of the model chain used for calculations - in particular explicitly accounting for near-field radionuclide retardation in bentonite and allowing consideration of non-linear sorption and colloid transport in the far-field.
- Improved and better justified databases for radionuclide release and transfer calculations (e.g. solubilities, sorption coefficients, etc.).
- Rock mechanical and thermal calculations to support conceptual layout studies which show how relatively small blocks of low-permeability basement can be utilised.
- Implementation of procedures which improve quality assurance (e.g. fully traceable calculation output, formalised peer review).
- Extensive investment of effort in model verification and validation, often as part of international studies, using natural analogues and via specific experiments.
- Updated reviews to put performance assessment results in perspective by comparison with other repository analyses and evaluation of other potential environmental hazards.

An analysis incorporating moderately conservative model assumptions and data (designated the Reference Case) indicates that peak radionuclide releases, due predominantly to Cs-135, would be more than two orders of magnitude below the regulatory guideline and 3-4 orders of magnitude less than the natural background in Switzerland. Effectively no releases would be expected within the first 10,000 years and the small releases which would occur would peak only after more than 100,000 years.
Overall system performance is dominated by the near-field - the critical roles of the host rock are physical protection of the engineered barriers and ensuring relatively low groundwater fluxes through the repository. In the Reference Case, a very conservative description of the features in which groundwater flows through the basement is assumed due to the limited database available - more realistic descriptions imply that radionuclide retardation in the geosphere could also play a major barrier role.

Uncertainty in the long-term behaviour of the repository system is taken into account by analysing a range of alternative scenarios. In particular, a Robust Scenario is defined in which bounding estimates of the effects of parameters and processes are obtained by making very conservative assumptions. Even the very pessimistic combinations of conservative parameters and model assumptions within this scenario do not lead to doses above the regulatory guideline.

The results of the Kristallin-I project demonstrate that the crystalline basement remains an attractive option for a HLW repository host rock. An exploration strategy has thus been devised for Phases II and III of site characterisation from the surface and underground, respectively. This initially involves high resolution seismic surveys and an array of angled boreholes in order to further clarify key questions concerning the lateral extent of suitable blocks within the crystalline basement. Given the date specified for the next major milestone in the HLW programme - Project Entsorgungsnachweis by the year 2000 - it is prudent to minimise the risks of delay or of geological complications by focusing Phase II on the location of an existing deep borehole which suggests favourable local conditions - i.e. Leuggern or Böttstein.

The methodology and databases developed within Kristallin-I form an infrastructure for analysis of other types of waste which would be included in a deep HLW repository (spent fuel and various types of long-lived intermediate-level waste) and, indeed, also for assessment of the potential of the Opalinus Clay as an alternative host rock. The Kristallin-I Reference Case forms a benchmark for comparison of the expected performance of different waste type/host rock combinations.

The documentation of system understanding within the scenario development procedure allows potentially important areas of uncertainty to be identified, which serves as a basis for deriving a more detailed list of research objectives. The sensitivity analysis within the Kristallin-I performance assessment allows the relative importance of individual parameters to be evaluated, thus forming a basis for assigning research priorities. The Kristallin-I technical documentation also forms the basis for deriving suitable information packages for the general public. As the HLW programme moves into a site characterisation phase for both crystalline basement and Opalinus Clay options, informing the population in the investigation areas becomes increasingly important. To promote public acceptance, the general procedures used should be as transparent as possible. The Kristallin-I project was planned with such output in mind and it is intended that it will provide a template for future studies of this type.
In terms of long-term development of a national HLW strategy, this confirmation that crystalline rock is sufficiently promising to merit further local exploration, and the selection of the preferred sites for this exploration are the key end-points of the Kristallin-I synthesis. It is important to note that the specific location chosen - even in the event that very positive results are achieved in the exploration - is unlikely to be the exact location of a deep repository. At a local scale, optimisation of shaft access etc. would certainly lead to new shaft areas; on a regional scale the long times available to potential implementation mean that comparison with alternative sites in crystalline host rock is not excluded; at a national scale, the option of disposal in clay is available; and at an international scale the attractiveness of joint projects is obvious. Although Kristallin-I and the following Project Entsorgungsnachweis 2000 will certainly not lead to immediate or even early implementation of a HLW repository, the goal of providing to the Swiss public a convincing and complete demonstration that we can, if necessary, dispose of HLW within our own borders remains a key element in our long-term waste management strategy.
ZUSAMMENFASSUNG


Die Hauptziele von Kristallin-I sind:
- Die Untersuchungen des PG’85 zu ergänzen und unter Berücksichtigung der jetzt vorhandenen, erweiterten geologischen Datenbasis auf den neuesten Stand zu bringen. Dies gilt ebenso für das verbesserte Verständnis der Mechanismen und Vorgänge, die für die Sicherheitsanalyse relevant sind.
- Dokumentation und Zusammenfassung der nun abgeschlossenen Phase I, um so die Grundlage zur Auswahl potentieller Gebiete für ein Standortnachweis-Projekt zur Verfügung zu stellen.
- Den aktuellen technischen Stand zur Entsorgungsplanung vorzulegen und Prioritäten für zukünftige Forschungsprojekte zu setzen.


Sowohl das direkte Untersuchungsgebiet als auch das nahegelegene Kristallin des Südschwarzwaldes wurden geologisch kartiert und hydrogeologisch/hydrochemisch untersucht.

Seit PG’85 wurde vor allem das geologische Verständnis des Grundgebirges vertieft und die Darstellung der daraus gewonnen Daten in einer Geodatenbasis für die Sicherheitsanalyse verbessert. Dies gilt vor allem für folgende Aspekte:

- Ein deutlich verbessertes tektonisches Modell der Region erlaubt die Beschreibung von zwei möglichen Unterregionen (Gebiete West und Ost) sowie Einblick in die Verteilung von Hauptstörungen innerhalb dieser Gebiete, was sich in einem statistischen Modell niederschlug.


- Die Ergebnisse aus Hydrochemie und Isotopen-Messungen wurden auf regionaler Basis zusammengestellt, um ein vernünftiges und einheitliches Bild der Grundwasserentwicklung als Folge der Wechselwirkungen zwischen Gestein und Wasser zu bieten; es stellt nicht nur die allgemeinen Fliessrichtungen des Grundwassers im Grundgebirge dar, sondern bildet ausserdem die Basis für die Definition der Referenzwässer an den zwei möglichen Standortgebieten.

- Die Analyse der möglichen geologischen Entwicklung über längere Zeiträume hinweg untermauerte die zwei Rahmenszenarien des PG’85 vor allem in Hinsicht auf die Quantifizierung von zu erwartenden Geländehebungen, Erosionsvorgängen und Bewegungen entlang unterschiedlich grosser Störzonen im betreffenden Gebiet mit einer Prognose bis zu einer Million Jahren.

Der Geosynthesebericht stellt alle bis zum jetzigen Zeitpunkt erhaltenen, wichtigen Informationen zusammen: als Ganzes stärkt diese Information das Vertrauen in die in den verschiedenen Fachgebieten (Tektonik, Hydrogeologie, Geochemie, usw.) entwickelten Konzepte.
Basierend auf der erwarteten geologischen Struktur wurde ein Endlager-Layout konzipiert, in dem die Lagerbereiche der Stollen für HAA im geringdurchlässigen Kristallingestein zwischen subvertikalen, regionalen Störzonen angelegt werden. Zum Beispiel würden für das Referenz-Abfallinventar (resultierend aus der geplanten 40-jährigen Betriebsdauer von 3 GW(e) installierter Kernkraftwerkleistung) 3 Lagerbereiche von jeweils 0.3 km² ausreichen. In einer Referenztiefe von ca. 1000 m unter der Erdoberfläche wären die Einlagerungsstollen dann von mindestens 100 m geringdurchlässigem Wirtgestein, mehreren 100 m höher durchlässigem Grundgebirge und hunderten von Metern Sedimenten überlagert. Die Endlagerplanung sieht auch Silos für die Einlagerung langlebiger mittelaktiver Abfälle vor, was aber im Rahmen von Kristallin-I nicht näher untersucht wurde.

In der strategischen Planung für die Abfallentsorgung der Schweiz werden auch alternative Szenarien für die Kernenergieproduktion sowie die Möglichkeit einer direkten Endlagerung künftig anfallender abgebrannter Brennelemente erwogen, was aber im Rahmen der Synthese Kristallin-I ebenfalls nicht näher diskutiert wird.

Wie in PG’85 dargelegt, werden zunächst Edelstahlkokillen mit verglasten HAA in massiven Stahlbehältern eingekapselt; diese werden horizontal in mit hochkompaktiertem Bentonit verfüllten Stollen eingelagert. Die für die Sicherheitsanalyse dieses Endlagerkonzeptes verwendeten Methoden und Ausgangsdaten haben sich seit PG’85 etwas weiterentwickelt:

- Aufnahme einer Methodik zur Szenarien-Analyse, die das Systemverständnis auf vollständige und nachvollziehbare Weise dokumentiert und eine logische Strukturierung der zahlreichen durchgeführten Berechnungen erlaubt.

- Verbesserung der konzeptionellen Modelle im Hinblick auf eine realitätsnähere Darstellung der untersuchten Systeme. Dies gilt vor allem für die Struktur wasserführender Systeme im Wirtgestein als Basis zur Modellierung des Radionuklidtransports.

- Ergänzung der für die Berechnungen benutzten Modellkette, insbesondere durch Einbeziehung der Rückhaltung von Nukliden im Bentonit und durch Abschätzung der nichtlinearen Sorption und des Kolloidtransports im Fernfeld.

- Verbesserte Datensätze für Nuklidfreisetzungs- und Transportberechnungen (z.B. Löslichkeiten, Sorptionskoeffizienten, usw.).

- Felsmechanische und thermische Berechnungen bestätigen das Endlagerkonzept und zeigen, wie relativ kleine Blöcke geringdurchlässigen Grundgebirges genutzt werden können.

- Massnahmen zur Verbesserung der Qualitätssicherung: z.B. vollständig nachvollziehbare Berechnungsergebnisse oder Prüfung durch unabhängige Experten (Peer-Reviews).
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Erheblicher Aufwand zur Verifizierung und Validierung der Modelle, oft im Rahmen internationaler Studien, durch Vergleich mit natürlichen Analoga und gezielte Experimente.

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Frühere Reviews wurden aktualisiert, um die Ergebnisse der Sicherheitsanalysen mit denen von ähnlichen Endlagerprojekten oder von Studien anderer möglicher Umweltrisiken zu vergleichen.

Eine als Referenzfall bezeichnete Analyse mit eher konservativen Modellannahmen und Ausgangsdaten zeigt, dass die Spitzenwerte der Strahlendosen aus Radionuklidfreisetzungen - verursacht vor allem durch Cs-135 - um mehr als zwei Größenordnungen kleiner als in den Richtlinien vorgeschrieben und somit 3-4 Größenordnungen unter der natürlichen Strahlenbelastung in der Schweiz liegen. Innerhalb der ersten 10'000 Jahre werden effektiv keine Freisetzungen erwartet, und erst nach über 100'000 Jahren erreichen die geringen Freisetzungen ihre Spitzenwerte.

Das Gesamtverhalten des Endlagersystems wird vorwiegend durch das Nahfeld bestimmt; das Wirtgestein trägt entscheidend zum physikalischen Schutz der technischen Barrieren bei und soll einen relativ geringen Grundwasserfluss durch das Endlager sicherstellen. Im Referenzfall wird aufgrund der beschränkten verfügbaren Daten eine sehr konservative Beschreibung der Grundwassersysteme im Grundgebirge angenommen. Alternative Modelle weisen auch der Rückhaltung von Radionukliden in der Geosphäre eine wichtige Barrierenfunktion zu.


Methoden und Datensätze des Projekts Kristallin-I bilden das Gerüst zur Analyse auch anderer Abfallarten, die in einem tiefliegenden HAA-Endlager eingelagert werden können (abgebrannte Brennelemente und verschiedene Arten langlebiger, mittelaktiver Abfälle), ebenso wie für die Einschätzung des Opalinustons als alternatives Wirtsgestein. Der Referenzfall Kristallin-I stellt eine Vergleichsbasis verschiedener Kombinationen von Abfalltypen und Wirtsgestein dar.


RESUME

L'actuelle stratégie de la Cédra prévoit l'élimination des déchets de haute activité et de moyenne activité à vie longue dans un dépôt final aménagé dans une formation géologique profonde. Le sous-sol cristallin du nord de la Suisse a été identifié pour servir de roche d'accueil potentielle à un dépôt final de ce type. En 1981, un plan devant se dérouler en trois phases a été élaboré et entrepris en vue de la caractérisation géologique. Le programme Cristallin I comprend une synthèse des résultats des recherches régionales de terrain de la Phase I, recherches qui ont d'ailleurs été récemment terminées. Cette synthèse se base largement sur le concept de dépôt final qui avait été présenté dans le Projet Garantie 1985 (PG'85; CEDRA 1985). En 1988, les autorités suisses chargées de la sûreté des installations ont présenté leur expertise du Projet Garantie; pour elles, PG'85 a démontré la faisabilité technique fondamentale de ce dépôt final et montré en plus que le concept de stockage final présenté pourrait garantir une sûreté suffisante pour les déchets vitrifiés de haute activité (DHA). Mais les données géologiques disponibles à l'époque étant limitées, les autorités ont exigé une preuve de site plus convaincante pour les possibilités de stockage final en Suisse. Dès 1988, on a donc procédé à des recherches sur des formations sédimentaires, simultanément aux études sur la roche d'accueil cristalline.

Le programme Cristallin I poursuit les principaux objectifs suivants:

- Compléter et actualiser les études du PG'85, en perspective surtout de la large base de données géologiques actuellement disponibles et de la meilleure compréhension des mécanismes et processus importants pour l'analyse de sûreté.

- Documenter la Phase I terminée et intégrer les résultats afin que les régions potentielles soient sélectionnées sur une base solide, dans le but de fournir la preuve du site.

- Préparer les données techniques les plus actuelles en matière de planification de la gestion nucléaire et établir les priorités des futurs projets de recherche.

Ce rapport donne une vue exhaustive de l'ensemble du projet. Il est complété par deux rapports techniques de synthèse, l'un contenant les résultats des études géologiques (THURY et al. 1994), l'autre documentant l'analyse de sûreté qui lui est liée (CEDRA 1994). Ces rapports de synthèse se fondent quant à eux sur de nombreuses publications plus spécialisées, parues pour la plupart dans la série des rapports techniques de la Cédra (NTB).

La sélection du socle cristallin du nord de la Suisse comme roche d'accueil potentielle s'est faite sur la base de critères tels que la bonne prévisibilité à long terme des conditions géologiques, les propriétés hydrogéologiques potentiellement favorables, la faible sismicité, l'absence de ressources naturelles exploitables, ainsi que les caractéristiques mécaniques et techniques (construction) favorables de la roche. La caractérisation régionale réalisée au cours de la Phase I a compris d'importantes analyses sismiques ainsi que la réalisation de sept forages profonds (1’300 à 2’500 m),
analysés en détail. La cartographie géologique et les investigations hydrogéologiques et hydrochimiques ont été réalisées dans la région de recherche et à côté, dans le sud de la Forêt-Noire où le socle cristallin affleure.

Les progrès réalisés depuis la parution du PG'85 sont évidents tant au niveau de la meilleure compréhension géologique du socle dans les zones concernées, qu'à celui de la représentation des informations ainsi acquises dans une base de données géologiques en vue de l'analyse de sûreté. Ils concernent notamment:

- La mise au point d'un modèle tectonique sensiblement amélioré de la région, permettant de décrire deux sous-régions potentielles (zones Ouest et Est) et de comprendre la répartition d'importantes zones de perturbations à l'intérieur de ces zones; un modèle statistique a alors pu être créé.

- La mise au point de toute une série de modèles hydrogéologiques, sur la base d'une synthèse de mesures hydrauliques plus étendues, tenant compte directement aussi du modèle structural développé et étant délimités par des mesures géochimiques et isotopiques régionales.

- La caractérisation détaillée de tous les systèmes aquifères observés dans les forages profonds. Les informations ainsi obtenues ont été regroupées en des représentations modélisées de trois systèmes. Ces descriptions sont étayées par de nouvelles études bibliographiques et permettent de définir les propriétés importantes de sorption et de diffusion matricielle de ces voies d'écoulement.

- Le regroupement des données hydrochimiques et isotopiques sur une base régionale, permettant d'offrir une image homogène de l'évolution des eaux souterraines sur la base d'interactions entre la roche et l'eau: Cela montre non seulement des modèles généraux d'écoulement des eaux souterraines dans le socle cristallin, mais forme aussi la base de la définition des eaux de référence des deux sites possibles.

- Enfin, l'analyse de l'évolution géologique possible à long terme a étayé les deux scénarios cadre du PG'85 - en perspective surtout de la quantification des soulèvements de terrain attendus, des phénomènes d'érosion et des mouvements le long des zones de perturbations de différentes grandeurs, dans la région concernée et au cours d'une période allant jusqu'à un million d'années.

Par ailleurs, le rapport de géosynthèse intègre toutes les informations clés obtenues jusqu'à présent, qui dans leur ensemble accroissent la confiance dans les concepts développés dans diverses branches techniques (tectonique, hydrogéologie, géochimie, etc.).
Sur la base de la structure géologique escomptée, une certaine conception du dépôt final a été définie: des zones de galerie destinées à l’emmagasinage des DHA sont aménagées dans le socle cristallin de faible perméabilité, entre les perturbations régionales subverticales. Pour l’inventaire de référence par exemple (déchets provenant de l’exploitation des centrales nucléaires de 3 GW(e) existantes, prévue sur une durée de 40 ans), il suffirait de disposer de trois zones de dépôt aménagées dans des blocs rocheux d’environ 0,3 km². A une profondeur référence d’environ 1’000 m au-dessous de la surface du sol, les galeries de stockage seraient recouvertes par 100 m au moins de roche d’accueil faiblement perméable, plusieurs centaines de mètres de roche cristalline plus fortement perméable et quelques centaines de mètres de roche sédimentaire. La conception de ce dépôt final comprend aussi des silos pour le stockage définitif des déchets de moyenne activité à vie longue, ce qui n’a toutefois pas fait l’objet d’études plus poussées dans le cadre du programme Cristallin I.

La planification stratégique de l’élimination des déchets en Suisse tient compte aussi d’autres scénarios de production d’énergie nucléaire, ainsi que de l’option du stockage final direct des futurs éléments combustibles usés, ce qui n’a toutefois pas fait l’objet d’études plus poussées dans le cadre de la synthèse du programme Cristallin I.

Comme on l’a présenté dans PG’85, les DHA vitrifiés seraient confinés dans une coquille en acier massif, placée dans un conteneur en acier inoxydable, lui-même emmagasiné dans des galeries horizontales, remplies de bentonite hautement compactée. Depuis le PG’85, les méthodes et bases de données utilisées pour l’analyse de sûreté de ce concept de dépôt final ont été quelque peu améliorées, notamment par:

- L’adoption d’une rigoureuse méthode de mise au point et d’analyse des scénarios, qui documente la compréhension du système de manière plus complète et réalisable et permet de structurer de manière plus logique les nombreux calculs effectués.

- L’amélioration du développement conceptuel des modèles, permettant de mieux représenter les systèmes étudiés, notamment en ce qui concerne la structure des systèmes aquifères dans la roche d’accueil, qui sert de base à la modélisation du transport des radionucléides à travers le dépôt final.

- L’extension des capacités de la chaîne de modèles utilisés pour les calculs - compte tenu notamment du retard des radionucléides du champ proche dans la bentonite; cela permet de considérer la sorption non linéaire et le transport des colloïdes dans le champ éloigné.

- Des bases de données améliorées et mieux justifiées pour calculer le relâchement et le transfert des nucléides (solubilités, coefficients de sorption, etc.).

- Des calculs géomécaniques et thermiques pour soutenir les études du concept, qui montrent comment utiliser des blocs rocheux relativement petits dans le socle cristallin faiblement perméable.
L'utilisation de procédures permettant d'améliorer l'assurance de la qualité (calculs entièrement réalisables, expertises par d'autres spécialistes de la gestion des déchets).

De considérables efforts pour vérifier et valider les modèles, dans le cadre souvent d'études internationales et en recourant à des analogues naturels et des expériences spécifiques.

L'actualisation des résultats des analyses de sûreté, afin de pouvoir comparer avec d'autres analyses de sûreté des dépôts finals et d'évaluer d'autres risques potentiels pour l'environnement.

Partant d'hypothèses de modèles et de données légèrement pessimistes (le cas de référence), une analyse indique que le relâchement maximum des radionucléides, dû surtout au Cs-135, serait de deux ordres de grandeur de moins que la valeur prescrite dans les directives, et inférieur de trois à quatre ordres de grandeur au taux d'irradiation naturel en Suisse. On ne prévoit en effet pas de relâchement au cours des 10'000 premières années; les faibles relâchements susceptibles d'apparaître n'atteindraient leur maximum qu'au bout de plus de 100'000 ans.

Le comportement global du système de dépôt final est dominé par le champ proche - la roche d'accueil contribue de manière essentielle à la protection physique des barrières techniques et garantit un écoulement relativement faible des eaux souterraines à travers le dépôt final. Dans le cas de référence, on suppose, sur la base de données restreintes, une description très pessimiste des structures dans lesquelles l'eau souterraine s'écoule à travers le socle cristallin - d'autres descriptions indiquent que la géosphère pourrait aussi jouer un rôle important en tant que barrière.

On tient compte de l'incertitude du comportement à long terme du système de dépôt final, en analysant toute une série d'autres scénarios possibles. On définit notamment un scénario robuste, pour lequel on dispose, sur la base d'hypothèses très pessimistes, d'estimations limites sur les effets des paramètres et des processus. Même la combinaison extrêmement pessimiste de paramètres et hypothèses de modèles pessimistes eux aussi, dans le cadre de ce scénario, ne conduit pas à des doses qui dépassent les valeurs prescrites par les autorités.

Il ressort des résultats du projet Cristallin I que le socle cristallin est une option d'accueil que l'on a retenue pour le dépôt final DHA. Une stratégie d'investigation a donc été mise au point pour les Phases II et III de la caractérisation du site depuis la surface et depuis le sous-sol. Pour commencer, cela comprend des analyses sismiques de résolution élevée et une série de forages inclinés, permettant de clarifier encore les questions clés concernant l'extension latérale de blocs adéquats à l'intérieur du socle cristallin. Vu la prochaine date la plus importante du programme DHA - Projet Preuve de l'élimination d'ici l'an 2000 -, il est prudent de minimiser les risques de retard ou de complications géologiques en concentrant la Phase II sur le site d'un forage profond existant, où l'on s'attend à trouver des conditions locales favorables (par exemple Leuggern ou Böttstein).
La méthodologie et les bases de données mises au point dans le projet Cristallin I forment une infrastructure destinée à l'analyse d'autres types de déchets, qui seraient emmagasinés dans un dépôt final profond DHA (éléments combustibles et divers types de déchets de moyenne activité à vie longue), ainsi qu'à l'évaluation des possibilités de l'argile à Opalinum considérée comme roche d'accueil potentielle. Le cas de référence du projet Cristallin I sert à comparer le comportement attendu de différentes combinaisons de types de déchets et de roche d'accueil.

La documentation de la compréhension du système dans le cadre du développement du scénario permet d'identifier des incertitudes pouvant être importantes. Cela sert de base à l'élaboration d'une liste plus détaillée d'objectifs de recherche. L'analyse de sensibilité réalisée dans le cadre de l'analyse de sûreté du programme Cristallin I permet d'évaluer l'importance relative de paramètres individuels, ce qui est à la base des priorités de recherche posées. La documentation technique de Cristallin I est aussi à la base d'aspects d'information pouvant être accessibles à un public plus large.

L'information de la population des régions de recherche prend toujours plus d'importance, vu que le programme DHA passe à la phase de la caractérisation du site, tant pour l'option du socle cristallin que pour celle de l'argile à Opalinum. Pour promouvoir l'acceptation publique, les procédures utilisées doivent être aussi transparentes que possible. Planifié dans cette optique, le projet Cristallin I doit fonder les futures études de ce type.

En perspective de l'évolution à long terme d'une stratégie DHA nationale, la synthèse Cristallin I a quelques points clés, notamment la confirmation du fait que la roche est suffisamment prometteuse et que donc d'autres investigations sont envisageables et qu'on peut procéder à la sélection des meilleurs sites. Mais il est important de noter que, même si les recherches donnent des résultats très positifs, le site spécifique choisi a peu de chance d'être le site qui sera retenu pour le dépôt final. Au niveau local, l'amélioration de l'accès au puits conduirait certainement à de nouvelles zones pour le puits. Au niveau régional, les longs espaces de temps disponibles pour la réalisation signifient qu'il n'est pas exclu de faire des comparaisons avec d'autres sites du socle cristallin; au niveau national, il est par ailleurs possible de construire un dépôt final dans l'argile; et au niveau international, c'est bien sûr la possibilité d'une collaboration qui s'impose. Bien que le programme Cristallin I et le prochain Projet Preuve de l'élimination 2'000 ne permettent certainement pas la réalisation immédiate ni même prochaine d'un dépôt final DHA, leur objectif consiste néanmoins à fournir à la population suisse la preuve convaincante et complète que nous pouvons, si nécessaire, construire le dépôt final DHA à l'intérieur de nos propres frontières, ce qui reste un élément clé de la stratégie à long terme que nous poursuivons en matière de gestion des déchets radioactifs.
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1 KRISTALLIN-I IN THE CONTEXT OF THE SWISS NUCLEAR WASTE MANAGEMENT PROGRAMME

1.1 Background

The management of wastes is increasingly recognised as a major challenge in modern society and great efforts are being made towards minimising waste production or recycling waste materials into useful products. Nevertheless, considerable quantities of wastes are produced which have no obvious further use or are too costly to recycle and which must therefore be disposed of. The disposal of wastes can have a negative environmental impact and hence must be carefully planned - particularly when the wastes are potentially hazardous or toxic. The precautions taken for the disposal of radioactive wastes are especially stringent and sophisticated repositories have been designed to ensure that these wastes are isolated safely from the environment for as long as they remain hazardous. This report documents the results of studies carried out to determine the suitability of the crystalline basement of Northern Switzerland as a host rock for a deep repository for highly radioactive wastes.

Switzerland is a relatively small country with a high population density and a wide industrial base. With a well developed economy, a secure energy supply is of considerable importance but, as it is poor in natural resources, Switzerland has to import about 80% of its primary energy requirements, predominantly in the form of petroleum products. Electricity covers about 20% of the energy demand; of this about 40% is supplied from nuclear power plants, with most of the rest being hydroelectricity.

The main source of radioactive wastes in Switzerland is nuclear power production. Nuclear power was first produced in 1969 and Switzerland currently has 5 nuclear power plants (pressurised water reactors and boiling water reactors) with a total capacity of around 3 GW(e). Most of the waste radionuclides produced during reactor operation are contained within the fuel itself; this may be prepared for direct disposal or reprocessed to recover usable uranium and plutonium, with the resulting wastes being solidified for subsequent disposal. To date, Swiss disposal planning has focused on wastes returned from foreign reprocessing plants; currently, however, the preferred strategy of the electricity supply utilities is to keep both options (reprocessing and direct disposal) open. Additionally, it is currently assumed for dimensioning of repository projects that there will be no expansion of the Swiss nuclear power programme and that the existing reactors will not be replaced at the end of their planned operational lifetime (40 years). This scenario leads to very low total volumes of high-level waste - complete reprocessing would yield about 500 m$^3$ total before packaging, resulting from ~3000 tonnes of spent fuel.

A further important source of nuclear wastes is the diverse use of radionuclides in medicine, industry and research (MIR wastes). Although the total radioactivity of such wastes is much less than that from nuclear power production, they are by no means trivial in terms of quantity and may pose particular problems due to their heterogeneity.
Wastes can be classified according to their radionuclide content, taking into account the type of radiation which they emit and the half-lives of the constituent radionuclides. This leads to the general terminology of low-level waste (LLW), intermediate-level waste (ILW) and high-level waste (HLW). In Switzerland, wastes are also classified according to their envisaged disposal route. Of the two planned repositories, one is intended for short-lived low- and intermediate-level wastes\(^1\), without significant amounts of long-lived radionuclides; the other is intended for high-level waste\(^2\) and intermediate-level waste containing higher concentrations of long-lived radionuclides\(^3\), which is broadly similar to the category of wastes often referred to as transuranic-containing waste (TRU)\(^4\) - even though the transuranics may not be the only long-lived nuclides in such waste. In this report, the abbreviation TRU is understood to signify long-lived intermediate-level waste. High-level waste from reprocessing is differentiated from spent fuel (SF)\(^4\) for direct disposal.

The precise cut-off in activity allowed in the L/ILW repository will be left open until safety criteria can be developed based on the repository design and the geological characteristics of the recently proposed site at Wellenberg. The concept for L/ILW disposal is described in detail elsewhere (NAGRA 1992).

An overview of the sources of wastes in Switzerland and the disposal concepts considered is presented in Fig. 1.1 and is discussed further in Chapter 2. This report focuses on the repository for co-disposal of high-level and long-lived intermediate-level wastes, with particular emphasis on the HLW which will contribute >99% of the initial total toxicity of emplaced wastes.

### 1.2 Legal and regulatory issues

The fundamental legal constraints on nuclear waste management in Switzerland are set by the Atomic Act of 23 December 1959 and the amendment thereto in the Federal Government Ruling of 6 October 1978. The Swiss Parliament has also recently passed a new Radiation Protection Act in which the most waste-relevant section is a clause stating that Swiss radioactive wastes should, in principle, be disposed of in Switzerland - although exceptions can be granted by the Federal Council. A complete revision of the Atomic Act is currently being drafted but this will not come into force before the year 2000.

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\(^1\) In German: schwach- und mittelaktive Abfälle - SMA
\(^2\) In German: hochaktive Abfälle - HAA
\(^3\) In German: langlebige mittelaktive Abfälle - LMA
\(^4\) In German: Brennelemente - BE
The first Atomic Act clearly places the responsibility for nuclear waste disposal with the producer of the wastes. The Ruling of 1978 further stipulates that "The general licence for nuclear reactors will be granted only when the permanent, safe management and final disposal of radioactive waste is guaranteed". No time limits were set in the Federal Government Ruling for carrying out the work necessary for providing the required guarantee and the Ruling did not affect reactors already in operation. However, in 1978/79, the Federal Department of Transport, Communication and Energy (EVED) decided that extension of the existing operating licences would be conditional on presentation of a project offering a guarantee of safe management and disposal of radioactive waste from nuclear power plants.

The safety conditions which the final repositories must satisfy are defined in the revised Guideline R-21 (HSK & KSA 1993) of the Federal Commission for the Safety of Nuclear Installations (KSA) and the Swiss Federal Nuclear Safety Inspectorate (HSK). Three Protection Objectives are defined:

Fig. 1.1: Waste sources and disposal options
- The repositories must ensure the safety of human beings and the environment from any harmful effects of ionising radiation. Accordingly, the central point is Objective 1, which states: "The release of radionuclides from a sealed repository subsequent upon processes and events reasonably expected to happen, shall at no time give rise to individual doses which exceed 0.1 mSv per year". By way of comparison, natural radiation exposure of the Swiss population results in an average radiation dose of almost 5 mSv per year, with a general range of approximately 1-10 mSv per year.

- Objective 2 provides a quantitative risk level for judging the consequences of low-probability scenarios: "The individual radiological risk of fatality from a sealed repository subsequent upon unlikely processes and events not taken into consideration in Protection Objective 1 shall, at no time, exceed one in a million per year." The direct radiological risk of fatality from a scenario is thus multiplied by the estimated probability of the scenario occurring and this product should not exceed one in a million per year when summed over all such scenarios\(^5\). For comparison, the dose limit of 0.1 mSv per year corresponds to a nominal risk of fatality of 5 in a million per year.

- Besides the safety aspects, the R-21 Guideline reflects the understanding that responsibility for disposing of radioactive wastes lies with today's beneficiaries of nuclear power and should not be passed on to future generations. This is expressed in Objective 3: "After a repository has been sealed, no further measures shall be necessary to ensure safety. The repository must be designed in such a way that it can be sealed within a few years." Once the repository has been sealed, it must thus be possible to "forget" the radioactive waste in the sense that it should not be necessary for future generations to concern themselves with it. There is thus no requirement for monitoring or retrievability of the waste.

In addition to the requirements formulated in these Protection Objectives, non-nuclear regulations must also be taken into consideration; these include international law, district planning, environmental protection, nature conservation, etc.

A popular referendum in 1990 led to a 10-year moratorium on further development of nuclear power, but this has not directly constrained the Swiss waste management programme.

1.3 Development of the disposal programme for high-level and long-lived intermediate-level wastes

As noted above, the producers of nuclear wastes are responsible for waste management (for all waste categories). Hence, the electricity supply utilities involved in nuclear power production and the Swiss Confederation (which is directly responsible

\(^5\) It should be noted that R-21 also states that "Processes and events with extremely low probability of occurrence or with considerably more serious non-radiological consequences, as well as intentional human intrusions into the repository system, are not required to be considered in the safety analysis". 
for wastes from medicine, industry and research) joined together in 1972 to form the "National Cooperative for the Disposal of Radioactive Waste" (NAGRA). Nagra is responsible for all preparations for the disposal of all categories of waste. Actual repository construction and operation will be carried out by sister organisations, such as the Genossenschaft für nukleare Entsorgung Wellenberg (GNW) which has already been founded to implement a repository for L/ILW. The responsibility for spent fuel reprocessing and transport, for waste conditioning and for interim storage at power plants remains directly with the utilities. A centralised conditioning plant and interim storage facility (ZWILAG) for all categories of waste is currently being planned by the utilities. A Federal Government facility (BZL) for storing wastes from medicine, industry and research is already in operation and will, in due course, be integrated into the ZWILAG facility.

Since the founding of Nagra, extensive work has been carried out on the development of disposal concepts and identification of potential sites for repositories. A first integrated assessment of disposal of nuclear wastes in Switzerland (VSE et al. 1978) established the fundamental concept of deep geological disposal of high-level waste and identified a range of potential host rocks including argillaceous sediments, evaporites and crystalline basement.

Site selection investigations for the HLW/TRU repository were concentrated in the northern part of Switzerland, due principally to the expected long-term tectonic stability of this region and its low seismicity. Host rock options were narrowed down to the crystalline basement and some of the overlying sedimentary formations. On the basis of available information, and taking into account requirements for geological stability and ease of construction of a deep repository, the crystalline basement was selected as first priority for investigation. A three-phase siting programme was conceived in which initial regional studies (Phase I) would lead on to more detailed investigation from the surface of a limited area (Phase II) and, eventually, to underground characterisation of a potential site (Phase III). Major components of the regional characterisation programme were extensive geophysical investigations and a series of deep boreholes in an identified study region which covered ~1200 km² (cf. THURY 1980; NAGRA 1983). The drilling campaign commenced in 1982 but was not completed until 1989, due to delays in licensing procedures.

The EVED requirement to guarantee the feasibility of safe disposal (cf. section 1.2 above) set the deadline for producing a suitable project of 31 December 1985, which resulted directly in the Project Gewähr 1985 study (PG’85; NAGRA 1985). The timescale specified meant that this study had to be produced before the full regional characterisation had been completed and hence it was based on a model geological database compiled predominantly from information provided by the first deep borehole at Böttstein.

Particular characteristics of the HLW repository concept developed in PG’85 are very deep (up to ca. 1200 m) in-tunnel disposal in crystalline basement rocks, which are overlain by a thick series of sediments. Geological isolation is complemented by a
series of engineered barriers, including a 25 cm thick steel canister and a layer of compacted bentonite over a metre thick. It should be noted that, for the purpose of the feasibility demonstration, there was no attempt to optimise design parameters. In this concept, TRU is emplaced in concrete-filled silos at a distance from the HLW emplacement tunnels.

The PG’85 study showed clearly that construction of the planned repository was feasible (Baumachbarkeitsnachweis) and that, for the expected evolution of the repository system, doses predicted using state-of-the-art models were far below the regulatory guidelines. Nevertheless, some open questions were identified which needed clarification before progressing beyond the basic concept feasibility demonstration presented in PG’85. In their review of this project (HSK 1987; KSA 1986), the authorities concluded that the proposed concept would provide sufficient safety (Sicherheitsnachweis), but that it should be more convincingly demonstrated that a suitable site with the assumed geological characteristics could be found (Standortnachweis). The government review also strongly recommended that the option of disposal in sedimentary formations be considered in more depth. Despite these caveats, the operating licences for the power plants were extended and the waste disposal issue was no longer tied directly to reactor operation.

1.4 Current plans for high-level waste management in Switzerland

Since PG’85, there have been significant developments in the HLW/TRU programme. The regional examination of the crystalline basement of Northern Switzerland has now been completed (Phase I as defined above) and this report overviews the results of this analysis. In parallel, sedimentary formations in Northern Switzerland are being examined as alternative host rocks and two intermediate reports summarising this work have been published (NAORA 1988; 1991). A final synthesis of this work, which identifies Opalinus Clay as the most promising formation for further investigation, has been completed and is in the final stages of documentation.

The key components and milestones in the HLW/TRU programme are summarised in Fig. 1.2. The completion of the regional analysis of the crystalline basement, documented in the Kristallin-I project, will be followed by detailed local characterisation of a potential siting area from the surface (Phase II). Parallel Phase II studies will be carried out at a single representative location in Opalinus Clay.

It is planned to deliver the proof of siting feasibility within an overall project establishing repository options by the year 2000 (Project Entsorgungsnachweis 2000 6). This would help to decouple the question of HLW disposal from other factors which will determine the future of nuclear power in Switzerland at the end of the current 10-year nuclear power development moratorium (cf. section 1.2).

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6) This project should include all three feasibility aspects noted above, namely construction, safety and siting (Baumachbarkeitsnachweis, Sicherheitsnachweis, Standortnachweis)
Fig. 1.2: Components of the HLW/TRU programme and identified milestones
Although no definition of the requirements for a *Standortnachweis* have been formulated in detail, it is clear that the emphasis will be different for crystalline and clay host rock options. For the crystalline host rock concept, the key question is the existence of sufficiently large blocks of low permeability rock in which a repository could be situated and the feasibility of developing a field programme to characterise an appropriate site. This has consequently been a topic examined in detail in Kristallin-I. The Opalinus Clay formation appears to be more homogeneous than the crystalline basement and hence basic geological questions may be less site-specific. However, studies aimed at demonstrating the basic feasibility and safety of constructing a repository in this rock (the *Baumachbarkeitsnachweis* and *Sicherheitsnachweis* mentioned above) have not yet been completed.

For both host rocks, it is clear that the *Entsorgungsnachweis* project, which will be based on exploration of potential siting areas from the surface, will not provide sufficient geological data to allow application for a repository construction licence. For this, extensive underground characterisation (Phase III) would be needed, which would, initially, involve driving of an access shaft to repository depth and construction of an underground test facility. However, the timescales for HLW disposal are very long; an operational repository is not required before 2020, at the earliest, due to planned storage times to allow the decay of radiogenic heat and optimised planning would push the implementation date to ~2050. Therefore, initiation of Phase III could be delayed for one or more decades. Optimisation of planning of interim storage and eventual disposal, from both a technical and an economic viewpoint, could lead to even longer delayed initiation of Phase III. The intervening period could sensibly be employed to investigate international disposal options for the very small amount of HLW involved in the Swiss programme. Such long-term plans are, however, very dependent on the evolution of the Swiss nuclear power programme and national/international political developments.

### 1.5 The Kristallin-I project

The timescale for PG'85 was set by legal requirements and this project therefore had to be submitted at a relatively early stage of the HLW regional investigation programme. Now that Phase I of the crystalline basement characterisation programme is complete, the Kristallin-I project has been established to provide a more comprehensive evaluation of this potential host rock.

The main objectives of Kristallin-I are:

1) To update and complement PG'85: documenting extended databases (particularly from the geological exploration), improving safety assessment models and carrying out further work on open issues either identified in PG'85 or arising from its review by the authorities.
2) To serve as a milestone in the HLW programme: formally completing Phase I by selecting potential areas for siting demonstration, developing a programme for Phase II field work and providing the background for a later comparison of crystalline and sedimentary host rock options.

3) To provide input for overall waste management planning: forming a benchmark for assessing inventory variants (spent fuel, various types of long-lived intermediate-level waste), allowing priorities to be re-assessed in the context of integrated performance assessment with a view to focusing future R&D work and, of increasing importance, contributing to public information on disposal projects.

The scope of Kristallin-I is set by these aims and constrained by the limitations imposed by available time and manpower (particularly in view of the higher priority of the parallel L/ILW repository project). Kristallin-I thus excludes detailed consideration of construction and operational procedures, as these were covered in PG'85 to a level sufficient for present purposes. The basic design of the engineered barrier system for HLW is taken directly from PG'85, with no consideration of alternative designs. Other topics which were excluded from the Kristallin-I analysis include studies of spent fuel and TRU construction and operational costs, safety during the operational phase, quality assurance/quality control of the waste packages, etc. Such studies do not contribute to the objectives specified for Kristallin-I; relevant technical studies in these areas are currently in progress and will be integrated into the subsequent Entsorgungsnachweis project.

The structure of the Kristallin-I documentation was selected with the aim of making access to the volume of information produced in this project as easy as possible. This present report is intended to provide a concise overview of the entire project. It is supported by two synthesis reports - one reviewing the geological work carried out (including studies of future exploration strategies) and the other summarising the associated performance assessment (THURY et al. 1994; NAGRA 1994 respectively). The synthesis reports are, in turn, supported by a wide range of publications, including over one hundred reports in the Nagra Technical Report (NTB) series.

1.6 Structure of this report

This report is intended to provide an overview of the entire Kristallin-I project and is aimed at a general technical audience which is not necessarily familiar with such integrated assessments. As such, it aims more to emphasise the rationale for the studies carried out and the integration of results, rather than attempting a comprehensive presentation and justification of all data and models used. Databases and results, when presented, are intended to be illustrative only and hence are not interpreted in full. For more details, the reader is referred to the synthesis reports mentioned above which are written at a more technical level and, additionally, provide full references to the more specialist background literature.
Following this introductory chapter, the basic repository concept is introduced in Chapter 2. Chapter 3 provides an overview of the geology of Northern Switzerland, with emphasis on the findings of Nagra’s regional investigation programme. Chapter 4 discusses the derivation of the data and models used for the performance assessment, focusing again on the input from the geological programme. Chapter 5 overviews the procedures used in the performance assessment and considers, in particular, the long-term evolution of the repository system and the approaches used to take into account uncertainties in model predictions. Chapter 6 summarises the results of the performance assessment and discusses the relative roles of the engineered and geological barriers and the requirements placed on a suitable site. The information presented in chapters 2-6 is integrated in Chapter 7 to provide an overall assessment of the suitability of the crystalline basement as a host rock for a HLW/TRU repository. It also discusses what further information would be required to support a Standortnachweis within the scope of an Entsorgungsnachweis project and a subsequent application for construction and operating licences and how such information could be obtained. The conclusions of the Kristallin-I project are summarised in Chapter 8, with particular emphasis on discussing the extent to which the aims set for this project (cf. previous section) have been achieved.
2 WASTE INVENTORIES AND DISPOSAL CONCEPT

2.1 Waste types and inventories

The deep geological repository considered in Kristallin-I is intended for disposal of high-level and long-lived intermediate-level radioactive wastes, which result predominantly from nuclear power production. Detailed specification of the waste inventory is inherently limited by the fact that only a small proportion of the total arisings has been produced to date. For planning purposes, however, a number of waste production scenarios have been specified (full details are given in ALDER & McGINNES 1994).

For Kristallin-I it is assumed that the existing nuclear power plants (3 PWRs: ~1.6 GW(e), 2 BWRs: ~1.3 GW(e)) have an operational lifetime of 40 years and that no further nuclear development takes place. All spent fuel is assumed to be reprocessed abroad and all resultant wastes returned to Switzerland (even though the extent of future reprocessing is not decided at present - cf. Section 1.1). High-level waste is assumed to be vitrified in a borosilicate glass matrix. The quantities of HLW arising from this scenario are given in Table 2.1.

The arisings must be considered to be model values as the actual inventories will vary with reactor operational parameters (e.g. burn-up, a parameter which tends to increase as improved techniques for core management are developed), fuel type and reprocessing procedures. In any case, for repository layout planning a reserve of about 50% can be built in. In PG'85, a much larger reserve was effectively included by assuming that the currently envisaged 120 GWa of nuclear power production would double (cf Table 2.1).

Kristallin-I considers only vitrified HLW in the performance assessment, although parallel studies of spent fuel are currently in progress. The definition of the geological requirements of a suitable site does, however, involve specification of the repository dimensions. For such layout studies, it is prudent to allow as much flexibility as possible in the total inventory of waste and hence alternative scenarios (mixed vitrified HLW/spent fuel and PG'85 base case) are also considered.

For example, an alternative scenario (designated HLW/SF in Table 2.1) is similar to the above with the single difference that no further reprocessing is assumed after current contracts (for ~1000 tU (tonnes uranium)) have expired. In this case, subsequent spent fuel is simply stored before direct disposal (Table 2.1).

---

1) PWR = Pressurised Water Reactor
BWR = Boiling Water Reactor
Total electrical power capacity is given in GW(e)
Table 2.1: HLW arisings from various waste management scenarios
(Data from ALDER & McGINNES 1994)

<table>
<thead>
<tr>
<th></th>
<th>120 GWa⁺ (HLW)</th>
<th>120 GWa (HLW/SF)</th>
<th>240 GWa (HLW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Kristallin-I)</td>
<td>(no further reprocessing)</td>
<td>(PG'85)</td>
</tr>
<tr>
<td>Vitrified HLW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>. packages</td>
<td>2693</td>
<td>707</td>
<td>5895</td>
</tr>
<tr>
<td>. volume, m³*</td>
<td>485</td>
<td>127</td>
<td>1061</td>
</tr>
<tr>
<td>Spent fuel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>. packages</td>
<td>-</td>
<td>1621</td>
<td>-</td>
</tr>
<tr>
<td>. volume, m³*</td>
<td>-</td>
<td>4036</td>
<td>-</td>
</tr>
</tbody>
</table>

*) Note that the volume given for vitrified HLW is only for the glass fabrication package and does not include the massive steel disposal canister. For spent fuel, it was assumed that the waste is directly conditioned in a Cu disposal container of the type considered in PG’85.

Again for layout studies, the volume of TRU to be included in the repository is required. The main source of such waste is reprocessing and the resulting volumes are very dependent on future operating practices of the companies carrying out this work (COGEMA and BNFL). The current estimate is that ~6 500 m³ of such wastes will be returned to Switzerland. To allow both for uncertainties in arisings from this source and for possible TRU from reactor operation and decommissioning, medicine, industry and research, a large reserve of 8 500 m³ is included to give a total volume of 15 000 m³.

The HLW composition is defined by the specifications set by the reprocessor and differs somewhat for waste produced by BNFL and COGEMA, but such differences are small relative to other uncertainties in the performance assessment databases. For the purposes of Kristallin-I, the COGEMA waste sort, as specified by a Nagra model composition, has been used, as was the case for PG’85.

The quantities of, and nuclide inventories in, spent fuel vary with reactor type (PWR or BWR), degree of burn-up and whether conventional UO₂ (uranium oxide) or MOX (mixed uranium/plutonium oxide) fuel is used. For calculating the inventories of reprocessing waste, ~3 600 tU of reference fuel is considered (PWR fuel with a burn-up of 33 000 MWD/tU). In reality, higher burn-up can be achieved and the actual arisings of spent fuel would probably be ~3000 tU for the 120 GWa scenario.
Compared with HLW, TRU is relatively heterogeneous and inventory definition is further complicated by the fact that it is coupled to final acceptance criteria specified for the LILW repository site (cf section 1.1). Based on the current model inventory, the TRU will contribute ~4% of the total activity of the HLW repository at the time of emplacement or ~1% of the equivalent toxicity.

A further factor influencing radionuclide inventories in the repository is the duration of storage prior to disposal. Much of the total activity of all the waste types considered is due to high concentrations of short-lived radionuclides and these will decrease considerably during times of a few years to tens of years. Although these short-lived radionuclides have little relevance for long-term safety (as they decay to insignificance before any release can occur), allowing decay before disposal minimises external radiation fields and temperatures, thus easing handling and thermal constraints on emplacement (i.e. allowing closer spacing of waste packages which decreases repository dimensions).

2.2 The repository system and how it functions over long timescales

The basic disposal concept involves emplacement of wastes in a purpose-built facility at a depth of about 1000 m below surface. Safety is based on the principle of multiple barriers provided by the waste-form (borosilicate glass), engineered structures (canister, backfill) and the geological environment. The series of multiple barriers for vitrified HLW is shown schematically in Fig. 2.1.

The system of engineered and natural barriers performs several roles, of which the main aspects are ensuring the physical integrity of the repository system over a long time period and minimising release rates of radionuclides to the human environment when the system eventually degrades.

The main contribution to ensuring physical integrity is very deep disposal in an old, stable crystalline basement. In addition to providing a physico-chemical environment conducive to longevity of the engineered barriers, the crystalline basement (plus the overlying sediments) isolates the repository from the effects of climate changes and surface catastrophes (e.g. hurricanes, dam-bursts, acts of war, etc.) and makes inadvertent human intrusion unlikely. Over long periods of time, some rock movement is to be expected, which is allowed for by surrounding the waste package by a thick backfill of plastic bentonite clay. In such an environment, the thick steel canister should remain unbreached for at least 1000 years - and probably much longer.

After the canister is breached, water will come into contact with the glass matrix, which will then begin to dissolve slowly (expected times for total dissolution being ~10^5 years or more). This dissolution will take place in an environment in which solute transport occurs predominantly by diffusion (due to the very low hydraulic conductivity of compacted bentonite) and in which the porewater chemistry varies little (buffered by the large quantities of iron corrosion products and bentonite) and ensures low solubility of many important radionuclides.
Release rates from the engineered barriers are further constrained by retardation processes, which reduce the rate of transport through canister corrosion products and compacted bentonite due to sorption on mineral surfaces. Transport through the geological barrier will occur predominantly via advective groundwater flow in fractures and other discontinuities in the rock. Such transport will be retarded by sorption and also by diffusion into stagnant porewater in the surrounding rock. Retardation in the near- and far-field\textsuperscript{2} not only delays the release of radionuclides but, if the transit time is long relative to the nuclide half-life, can also greatly reduce concentrations due to radioactive decay (assuming the nuclide is not continuously produced by a longer-lived parent).

Concentrations are also reduced greatly due to dilution - this will occur as radionuclides carried by the low fluxes of water through the host rock mix into larger flows through more permeable surrounding rocks, overlying aquifers and surface water bodies. Radionuclides released to the accessible environment can pass into the food chain and give rise to a resultant radiation dose to the surrounding populace. As such releases occur only in the distant future, there is a large uncertainty as to how human society and the biosphere itself may have changed. Nevertheless, doses to man are calculated using a simplified set of biosphere assumptions (based largely on conditions today) in order to allow the potential radiological significance of releases to be evaluated.

\textsuperscript{2} The near-field is defined as the engineered barriers and the area of surrounding rock which is significantly perturbed by the presence of the repository. The far-field thus consists of the unperturbed rock between the repository and the near-surface environment (the biosphere). As the extent of the perturbed zone will be small, the terms far-field and geosphere tend to be taken as synonymous.
Safety barrier system for high-level waste

Glass matrix (in steel mould)
- Low corrosion rate of glass
- High resistance to radiation damage
- Homogeneous radionuclide distribution
- Corrosion products take up radionuclides

Steel canister
- Completely isolates waste for > 1000 years
- Corrosion products act as a chemical buffer
- Corrosion products take up radionuclides

Bentonite backfill
- Long resaturation time
- Low solute transport rates (diffusion)
- Retardation of radionuclide transport (sorption)
- Chemical buffer
- Low radionuclide solubility in pore water
- Colloid filter
- Plasticity (self-healing following physical disturbance)

Geological barriers
Repository zone:
- Low groundwater flux
- Favourable hydrochemistry
- Mechanical stability
Geosphere:
- Retardation of radionuclides (sorption, matrix diffusion)
- Reduction of radionuclide concentration (dilution, radioactive decay)
- Physical protection of the engineered barriers (e.g. from glacial erosion)

Fig. 2.1: The safety barrier system for disposal of vitrified high-level waste
3 GEOLOGICAL CHARACTERISATION OF THE CRYSTALLINE BASEMENT OF NORTHERN SWITZERLAND

3.1 Background

Our ability to develop a HLW repository concept which will ensure safety until waste toxicity has decreased to background levels - in the order of $10^6$ years\(^1\) - depends very much on our knowledge of the geological structure of Switzerland (Fig. 3.1). The present mountainous terrain was established during the Alpine orogeny which was initiated ~100 million years ago and which included not only building of the Alps but also formation of the Rhine Graben, updoming of the Black Forest, sinking of the Molasse Basin and development of the Folded Jura. It is observed that the Alps are still being uplifted by 1 - 1.5 mm per year in relation to the Molasse Basin - either due to a continuation of this orogeny or remnant isostatic uplift. In any case, it is prudent that a HLW repository be sited well away from such areas of major potential uplift and associated faulting (or movement along existing faults).

Important functions of the geological environment in terms of ensuring adequate repository performance over long time periods are:

1) Physical protection of the engineered barriers from natural perturbations (e.g. extreme weather/climate variations, erosion, earthquakes, etc.) and from deliberate or accidental human intrusion.

2) Hydrogeological/geochemical protection of the engineered barriers by ensuring that fluxes of groundwater through the repository area are low and that such groundwater is chemically favourable to engineered barrier longevity and low radionuclide solubility (relatively low ionic strength, near-neutral pH, chemically reducing).

3) Delay of the time of release and reduction in the concentrations of any radionuclides escaping from the repository before they reach the biosphere due to low groundwater flow rates, high radionuclide retardation, dispersion, dilution and radioactive decay during transport.

In addition, from a practical point of view, it must be possible to construct and operate the repository safely in this environment using present-day technology at acceptable costs.

These considerations led to the selection of the crystalline basement of Northern Switzerland as a potential host rock (cf. Table 3.1). This report focuses entirely on the crystalline basement option; potential sedimentary host rocks are being investigated in parallel and progress in this work has been reported elsewhere (NAGRA 1988; 1991).

\(^1\) After $\sim 10^6$ years, the toxicity of the Kristallin-I inventory of HLW is similar to that of a small U ore body of the type found in the Black Forest (NEALL 1994)
Fig. 3.1: Map of Northern Switzerland and adjacent areas showing major geological units.
Table 3.1: Factors leading to the selection of the crystalline basement of Northern Switzerland as a potential host rock

- Old, well consolidated basement (good long-term predictability over periods ~1 Ma)

- The hydrogeology of a basement overlain by sediments can be favourable

- The gravel aquifers in the discharge area and the river Rhine offer a large dilution potential

- The geochemical conditions are expected to be favourable

- Natural resources are minimal (a possible exception is geothermal energy)

- Low seismicity of the area

- Many foreign disposal projects are based on a crystalline host rock and there is therefore a lot of international experience in this area, as well as an extensive database which is partly applicable to the Swiss situation

- Granite and gneiss are attractive rock types from an engineering point of view

3.2 The Nagra regional investigation programme

As noted in Chapter 1, a three-phase strategy for characterisation of the host rock was adopted. Identification of a specific region of Northern Switzerland for Phase I investigation has been discussed in THURY (1980). The boundaries of this region are set by the national border in the north, the increasing depth of the crystalline basement in the south and areas of increased seismic activity and tectonic complexity in the east and west (Fig. 3.2).

The geological information identified as being most important for assessing the suitability of the crystalline basement is listed in Table 3.2. The resultant regional investigation of the crystalline basement constituted a major programme extending over 10 years and costing ~250 million SFr. Major components of this programme (Fig. 3.2, Table 3.3) were extensive seismic surveys and a series of 7 deep boreholes (~1300 - 2500 m deep).
Fig. 3.2: The Phase I region studied in Northern Switzerland showing seismic lines and the location of deep boreholes drilled by Nagra during this project

Table 3.2: Geological information required for assessing the suitability of the crystalline basement for hosting a HLW repository

- Location/size of low permeability blocks of host rock
- Water flux through potential repository locations and its spatial distribution
- Hydrochemistry of deep groundwater
- Regional groundwater flow rates and paths
- Detailed description of features in which groundwater flow occurs
- Specification of the extent of dilution between potential repository locations and identified groundwater discharge regions
- Predictions of how the properties of the geological barrier will evolve over time periods ~1 Ma
Table 3.3: Overview of the Phase I geological characterisation of the Northern Swiss crystalline basement

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Key components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep boreholes (7)</td>
<td>- Core logging and core sample analysis</td>
</tr>
<tr>
<td></td>
<td>- Borehole geophysical logging</td>
</tr>
<tr>
<td></td>
<td>- Hydraulic packer tests</td>
</tr>
<tr>
<td></td>
<td>- Fluid logging (electrical conductivity and temperature)</td>
</tr>
<tr>
<td></td>
<td>- Water sampling and analysis</td>
</tr>
<tr>
<td></td>
<td>- Long-term monitoring</td>
</tr>
<tr>
<td></td>
<td>- Rock mechanics measurements</td>
</tr>
<tr>
<td>Geophysics</td>
<td>- 3 vibroseisimcs campaigns</td>
</tr>
<tr>
<td></td>
<td>- Refraction seismics</td>
</tr>
<tr>
<td></td>
<td>- Gravimetry</td>
</tr>
<tr>
<td></td>
<td>- Aeromagnetics</td>
</tr>
<tr>
<td>Regional hydrochemistry/hydrogeology</td>
<td>- Long-term monitoring of 7 mineral/thermal springs and wells</td>
</tr>
<tr>
<td></td>
<td>- Hydrochemical sampling of over 100 springs and wells</td>
</tr>
<tr>
<td>Geological mapping</td>
<td>- Region Kaisten-Zurzach</td>
</tr>
<tr>
<td></td>
<td>- Northern Switzerland (map compilation)</td>
</tr>
<tr>
<td></td>
<td>- Black Forest</td>
</tr>
<tr>
<td>Neotectonics</td>
<td>- Tectonic studies</td>
</tr>
<tr>
<td></td>
<td>- Microseismics measurement network</td>
</tr>
<tr>
<td></td>
<td>- Geodesic measurements</td>
</tr>
<tr>
<td></td>
<td>- Geomorphology studies</td>
</tr>
<tr>
<td></td>
<td>- Stress measurements</td>
</tr>
</tbody>
</table>

The following sections summarise the key findings from the regional investigation programme relevant to evaluation of the crystalline basement as a potential repository host rock.
3.3 **Overview of the geology of the crystalline basement**

The crystalline basement, which is exposed north of the Rhine in the Black Forest, extends to the south under a series of sedimentary formations. Fig. 3.3 illustrates the major structural components influencing the location of potential siting areas in Northern Switzerland. Key components are the regional graben structures: the Rhine Graben, the Bodensee Graben and the East-West Permo-Carboniferous Trough (PCT) which transects the region. This PCT was, in fact, discovered during the Nagra regional investigation programme and its presence considerably limits the potential siting areas within this region. The crystalline basement is too deep for repository construction either under or south of the PCT and hence potential sites are restricted to within two smaller areas between the Trough and the national border - denoted Area West and Area East (cf. Fig. 3.3). Major sub-vertical fault zones, which are clearly expressed in exposures in the Southern Black Forest and can be partly identified by seismics beneath the sedimentary cover, are also important structural features. These fault zones represent the largest members of a continuous distribution of structural discontinuities in the basement, which can be assigned to distinct families reflecting their origins or can be classified according to their size (width and lateral extent). Predominantly based on analysis of outcrops in the Black Forest, a model of the distribution of major faults has been derived which indicates that large blocks exceeding 1 km² lying between such zones are expected to be rare but that medium-sized blocks (~0.3 - 0.5 km²) should be reasonably frequent.

Key input was provided by extensive analysis carried out in the deep boreholes (cf. Fig. 3.4). In general, there is a good correlation between the crystalline rock types identified in boreholes penetrating the crystalline basement in Northern Switzerland and those observed in outcrops in the adjacent Southern Black Forest. These are predominantly Variscan² (granites) and metamorphic rocks of sedimentary origin (paragneisses). A range of different types of dyke also occurs, of which aplites, pegmatites and lamprophyres are most common.

The crystalline rocks have been subjected to extensive regional alteration, including processes due to dyke intrusion, high- and low-temperature cataclasis³ and hydrothermal activity (temperatures up to 400 °C), and surface weathering.

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² Variscan refers to an orogenic (mountain-building) event which occurred over the period 340-280 Ma b.p.
³ Mechanical rock fracturing associated with dynamic metamorphism or faulting
Fig. 3.3: Major structural features in the Kristallin-I investigation region. Red lines show locations of major fault zones; Mesozoic/Tertiary uncovered

In addition, hydrothermal ore mineralisations (including barite, fluorite, sphalerite, galena, pyrite, pitchblende, calcite and quartz) are observed in the Black Forest but, as yet, these have been encountered in the basement of Northern Switzerland only very rarely - possibly due to their uneven distribution and the low probability of drilling through localised, sub-vertical veins.

Flow is localised in distinct water-conducting features in the crystalline rock. The undisturbed rock matrix has a hydraulic conductivity which is far less than that in specific flow zones. There is some indication of connected porosity in the rock matrix, but solute transport is dominated by diffusion ("matrix diffusion") rather than advection.

Based on observations of exposures in the Black Forest and core analyses from the Northern Swiss crystalline basement, three main types of such water-conducting features are identified:

a) cataclastic zones (faults of different sizes)
b) zones with open joints
c) fractured aplite/pegmatite dykes and aplitic gneisses
Geological overview

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>System</th>
<th>Member</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Tertiary</td>
<td>Münsterbäke</td>
<td>261</td>
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<tr>
<td>200</td>
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<tr>
<td>1400</td>
<td>Tertiary</td>
<td>Münsterbäke</td>
<td>431</td>
</tr>
</tbody>
</table>

Fig. 3.4: Böttstein borehole: Geological overview, testing and sampling programme. The Nagra deep boreholes provided key input for analysing the crystalline basement of Northern Switzerland. The figure summarises the geology observed in the first of these boreholes drilled at Böttstein and indicates the various tests carried out in this hole.
Examples are shown in Fig. 3.5. Each has a particular structure and associated mineralogy of fracture infill minerals/altered wallrock depending on its history of hydrothermal alteration.

Ongoing alteration and the formation of open channels in water-conducting features (predominantly in cataclastic matrices) by partial dissolution of infills and deposition of minerals such as calcite, quartz, fluorite, barite, siderite and clay minerals is consistent with present-day hydrochemistry.

3.4 Hydrogeology and hydrochemistry

The main hydrogeological features of the investigation area are the series of aquifers and aquitards in the overlying sediments; the major structural components of the crystalline basement and the Permo-Carboniferous Trough and the regional topography (highs to the north in the Black Forest and to the south in the Alps). Detailed hydrogeological measurements within the crystalline basement in this area are effectively restricted to those carried out in the Nagra boreholes. These data (e.g. Fig. 3.6) indicate that, at least in Area West, the basement can be subdivided into an upper (several hundred metres thick) higher-permeability domain (HPD) and an underlying low-permeability domain (LPD).

These hydrogeological measurements, combined with the structural information presented in the previous section, led to the conceptual model of the crystalline basement of Northern Switzerland illustrated in Fig. 3.7. A repository would be located in the LPD where groundwater fluxes are expected to be quite low and localised in distinct water-conducting features. The same features would occur in the steeply dipping major water-conducting faults and the higher-permeability domain of the basement with a higher frequency and larger mean transmissivities.

The sediments of the overburden and the Permo-Carboniferous Trough vary widely in terms of hydraulic properties - ranging from local aquifers to very low permeability aquitards. Key information on the influence of such sediments on groundwater flow in the basement is provided by analysis of hydrochemical and isotope hydrological data.

Water samples from the crystalline basement and adjacent units have been analysed from the Nagra deep boreholes, thermal water boreholes at Zurzach and Säckingen and springs in the Black Forest. Four distinct water types can be identified (cf. Fig. 3.8):

a) "Recharge waters" in the Black Forest which are alkaline earth bicarbonate type with salinities \(<-0.2 \text{ g l}^{-1}\).

b) "Eastern group" sodium-carbonate-sulphate type sampled from the Siblingen borehole with salinities \(\sim 0.5 \text{ g l}^{-1}\).
Fig. 3.5: Illustrations of water-conducting features in the crystalline basement

a) Aplite dyke with open fractures. Sample KAI 1091.70 from the Kaisten borehole, width of photograph equivalent to 9 cm

b) Cataclastic zone of the high-temperature phase. Rounded fragments of granite are embedded in a dark, quartz-hematite-rich cataclastic matrix. Sample BOE 764.80 from the Böttstein borehole, width of photograph equivalent to 10 cm

c) Cataclastic zone of the low-temperature phase. Gneiss fragments are embedded in a clay-rich cataclastic matrix. Sample LEU 257.50 from the Leuggern borehole, width of photograph equivalent to 8 cm

d) Open joint of the low-temperature phase. Fracture coating comprises mainly clay minerals and feldspars in the adjacent wallrock are altered to clay minerals. Sample SIB 886.59 from the Siblingen borehole, width of photograph equivalent to 6 cm
Fig. 3.6: Example of hydrological data derived from measurements in the Nagra deep boreholes
Fig. 3.7: Diagrammatic representation of the conceptual model of the crystalline basement, Area West

- Low-permeability domain of crystalline basement
- Higher-permeability domain of crystalline basement
- Major water-conducting faults
- Mesozoic sedimentary cover
- Permo-Carboniferous Trough
- Rhine river / Quaternary gravel

Water-conducting features (transmissive elements):
(a) cataclastic zones
(b) jointed zones with open joints
(c) fractured dykes
c) "Western group" sodium-sulphate waters with salinities in the range of 0.9 - 1.4 g l\(^{-1}\) which occur in the western part of the investigation region, north of the Permo-Carboniferous Trough represented by samples from the Zurzach, Leuggern, Böttstein and Kaisten boreholes.

d) A "Saline group" of Na-Cl waters with a wide range of salinities. Samples from the crystalline basement (Leuggern, Böttstein, Weiach, Schafisheim, Säckingen) have salinities between \(\sim 1.5\) and 13 g l\(^{-1}\) (the salinity range in adjacent sediments (Riniken, Weiach) is from \(\sim 10 - 120\) g l\(^{-1}\)).

There are many indications from the hydrochemistry that these groups represent gradual evolution in water chemistry during long transit times through the crystalline basement with the salinity increase resulting from slow rock/water interaction (and only a very limited amount of mixing with saline sedimentary waters). This is supported by analysis of isotopic and noble gas measurements, which indicate that the
"recharge" waters are relatively young, the eastern waters infiltrated between 17 and 70 thousand years ago and the western waters represent infiltration over 70 thousand years ago. Although they cannot be modelled to the same extent, indications from hydrogen and oxygen isotope measurements and concentrations of dissolved He indicate that the saline waters from the crystalline basement are even older.

The hydrochemical analysis provides the following input for the development of a regional hydrogeological model of the crystalline basement of Northern Switzerland:

a) Indications that recharge is in the Southern Black Forest, with water in the north-eastern part of the region being younger than that in the west and that exfiltration from the basement occurs into the gravels of the Rhine.

b) Hydrochemical signatures and isotopic evidence consistent with evolution of most waters entirely within the basement; input of waters from overlying sediments or the Permo-Carboniferous Trough appears to be limited and probably localised.

c) The presence of saline waters of great age indicating areas of restricted circulation.

On a smaller scale, the relatively constant groundwater chemistry in samples taken from ranges of depths indicates that the various water-conducting features from which they are taken are reasonably well interconnected.

A series of mathematical models is used to examine possible hydrogeological conditions on a range of a spatial scales (Fig. 3.9). On the largest scale (~1000 km²; cf. Fig. 3.10), the crystalline basement is represented by an equivalent porous medium with only the upper and lower zones of relatively high and low permeability distinguished. Information on the topography of the basement is input directly, as is the assumed existence of an area of higher permeability (tectonically disturbed) crystalline rock in the vicinity of the PCT. The model initially assumes no hydraulic connection between the basement and either the PCT or the overlying sediments. This model is able to simulate a regional flow system with recharge in the Black Forest and flow through Area East and then Area West in a manner which is generally compatible with the geochemical observations noted above (Fig. 3.10).

A more detailed local hydrogeological model is used to examine water flow on a smaller spatial scale. In this, all major water-conducting faults (MWCFs) are directly represented based on the idealised model of major fault distribution (cf. section 3.3 above), with a range of assumptions as to the proportion of such faults which would be hydraulically active. Although the idealised nature of the fault distribution means that it cannot be related to a specific geographical area, there are indications that representations in which only a small proportion of faults are hydraulically active are more consistent with observed head profiles in boreholes.
<table>
<thead>
<tr>
<th>Conceptual Model</th>
<th>Numerical Models</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of crystalline basement</td>
<td>Scale</td>
<td>Equivalent porous medium (EPM)</td>
</tr>
<tr>
<td>Regional (≈ 1000 km²)</td>
<td></td>
<td>Hybrid:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Discrete elements (MWCF)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Equiv. porous medium (HPD+LPD)</td>
</tr>
<tr>
<td>Local (≈ 50 km²)</td>
<td></td>
<td>Fracture network</td>
</tr>
<tr>
<td>Block (≈ 0.25 km²)</td>
<td></td>
<td>Water-conducting feature/Transmissive element (TE)</td>
</tr>
</tbody>
</table>

1. Upper crystalline-rock domain; designated as higher-permeability domain (HPD) in area West
2. Lower crystalline-rock domain; designated as low-permeability domain (LPD) in area West

Fig. 3.9: Models used to examine the hydrology of the crystalline basement of Northern Switzerland
The "block-scale" model which examines a single low-permeability domain block between major water-conducting faults is even more idealised and is based on networks of fractures which are generated stochastically from various models of the distribution, size and hydraulic properties of water-conducting features within a block of low-permeability domain. This model allows the heterogeneity of flow through a repository zone to be examined.

3.5 **Long-term evolution of the crystalline basement**

The siting region in Northern Switzerland was specifically chosen for its low seismicity and relatively low tectonic activity and, in the performance assessment, it is assumed that no significant changes in the safety-relevant properties of the crystalline basement occur over the timescales for quantitative analysis (in the order of a million years).
In reality, changes in the geological environment are to be expected which, although unpredictable in detail, can be bounded based on an understanding of the tectonic evolution of the important structural features of the region and assessment of current tectonic activity (neotectonics). Extensive analysis has confirmed that the two extreme supraregional tectonic evolution scenarios\(^4\) presented in PG'85 are still valid (i.e. the two alternative interpretations based on assumptions of whether the Alpine orogeny has ended or not).

The tectonic evolution scenario has a direct influence on regional hydrogeology, principally due to alteration of topography through differential uplift and subsequent river erosion and to changes in overburden via these processes. The depth of the repository and the presence of overlying sediments will, however, tend to minimise the hydrogeological perturbations in the vicinity of the repository caused by such evolution. As long as the general groundwater flow pattern of the region is preserved, the hydrochemistry is likely to change little, being set by the same slow rock/water interactions. The stability of this flow pattern is indicated by sensitivity analysis of the regional scale model discussed above.

Tectonic activity will result in movement along fault zones. These movements are expected to be concentrated in existing faults, especially those of regional scale. Movement along the smaller fault zones within an LPD block is expected to be <1 m in \(10^6\) years, which should not cause unacceptable loss of engineered barrier performance - especially as emplacement of canisters in such zones will be avoided. No formation of new major faults is to be expected. A range of further evolution scenarios (e.g. volcanism) can be postulated (Table 3.4), but these are considered to be very improbable and are discussed only qualitatively.

Very extensive changes in the near-surface environment will be caused by the scenarios considered above. From the point of view of repository performance assessment, the key factors are the extent to which surface dilution and the biosphere are affected. These factors are also influenced by other long-term effects - particularly climatic changes. Relative to most other processes of interest, climate changes rapidly and can vary between extremes of cold/heat and dryness/wetness on a timescale set predominantly by cycles of glaciation. Although extensive analysis of past glaciations has led to identification of regular cycles in climate, extrapolation of such cycles into the future is complicated by anthropogenic perturbations which could, potentially, over-ride natural driving forces. Nevertheless, even though the progress of future climatic change cannot be predicted, extremes of future climate are not expected to lie outwith those observed in the past. A set of climatic and altered near-surface environment scenarios are explicitly considered in the performance assessment.

\(^4\) Here the term "scenario" is used in a more general way than in the performance assessment scenario analysis described in Chapter 5. In the latter case, the features, events and processes comprising a "geological evolution scenario" are combined with others describing the behaviour of the engineered barriers and biosphere in order to derive an evolution scenario for the entire repository system.
Table 3.4: Geological evolution scenarios and their possible influence on a repository
(- irrelevant, 0 low relevance, x important, xx very important; parenthesis indicates low probability)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Near-field geosphere</th>
<th>Far-field geosphere</th>
<th>Hydro-/biosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety-relevant aspects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plutonism</td>
<td>(XX)</td>
<td>(XX)</td>
<td></td>
</tr>
<tr>
<td>Volcanism</td>
<td>(XX)</td>
<td>(XX)</td>
<td>(XX)</td>
</tr>
<tr>
<td>Hydrothermal activity, diagenesis</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Regional vertical movements</td>
<td>-</td>
<td>X</td>
<td>XX</td>
</tr>
<tr>
<td>Regional horizontal movements in overburden</td>
<td>-</td>
<td>(X)</td>
<td></td>
</tr>
<tr>
<td>Movements along large fault zones</td>
<td>XX</td>
<td>0</td>
<td>(X)</td>
</tr>
<tr>
<td>Movements along small fault zones</td>
<td>X</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Seismicity</td>
<td>(X)</td>
<td>(0)</td>
<td>0</td>
</tr>
<tr>
<td>Exogenous scenarios</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glacial/interglacial</td>
<td>-</td>
<td>X</td>
<td>XX</td>
</tr>
<tr>
<td>Warm - wet</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Alternating - wet</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Arid</td>
<td>-</td>
<td>XX</td>
<td>X</td>
</tr>
<tr>
<td>Meteorite impact</td>
<td>(XX)</td>
<td>(XX)</td>
<td>(XX)</td>
</tr>
</tbody>
</table>

Legend:  
— insignificant  
0 minimal significance or effect  
X important effect  
XX very important effect  
( ) possibility of occurrence very low
3.6 **Complementary geological investigations**

The regional investigation programme described in previous sections is complemented by other studies of crystalline rock carried out in Switzerland and abroad.

Of most importance are the experiments carried out at the Grimsel Test Site (cf. Nagra/BGR/GSF 1985). Since construction was completed in 1984, this facility has been used for carrying out a wide range of experiments to measure relevant properties of crystalline rock and to develop techniques for its characterisation. It is planned to continue work at this location until, at least, 1996.

Nagra also participated actively in the Swedish underground test facility at Stripa and is now contributing to the projects commencing at Åspö. Formal and informal collaboration agreements also provide input from other crystalline rock test facilities (e.g. URL in Canada, Tono and Kamaishi in Japan) and from regional investigation programmes (e.g. Finland, Sweden, Canada, etc.).

A number of natural analogue projects have also directly examined crystalline rocks - in particular the studies of the uranium mine at Menzenschwand (HOFMANN 1988) and within the international Poços de Caldas Project (CHAPMAN et al. 1991).

Finally, it should be noted that Nagra maintains a general watching brief on characterisation work carried out on crystalline rocks (usually associated with civil engineering projects) - particularly in Switzerland. Review of the literature and direct contact with the geologists involved provides valuable generic information (e.g. rock-mechanics data).

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5) "Natural analogues" are natural (or archaeological) systems which involve processes similar to those considered in repository performance assessment
4 PERFORMANCE ASSESSMENT: MODELS AND DATABASES

The main aims of the Kristallin-I performance assessment are:

- To re-evaluate the crystalline basement of Northern Switzerland as a host rock for a HLW repository.
- To improve understanding of the roles of the engineered and geological barriers.
- To determine key geological characteristics and parameters which need to be considered in planning site characterisation.
- To develop and test a more complete safety assessment methodology and tool kit.

In this Chapter, the models and databases used to describe the geological and engineered barriers are presented; Chapter 5 describes the procedures used in performance assessment and the computer codes used to quantify radionuclide release and transport.

4.1 Repository location and layout

As previously indicated in Fig. 3.7, it is assumed that the repository will be located in blocks of low-permeability domain (LPD) basement which are geotechnically suited for construction. These will lie between major water-conducting faults (MWCF) which are assumed to constrain the layout. As the presence of LPD has been demonstrated only in Area West, this is taken as the reference repository location for the performance assessment.

For the PG’85 reference case (~6000 HLW canisters; 40 m separation of emplacement tunnels), an emplacement area of ~1.4 km$^2$ would be required which, if placed in a single block with a respect distance$^1$ of 100 m from the major water-conducting faults, would require a total area of ~1.9 km$^2$. The lower inventory of waste for the Kristallin-I reference scenario (~3000 HLW canisters) would reduce this requirement to ~1 km$^2$ for a 40 m tunnel separation (including 100 m respect distance from major water-conducting faults) and to ~0.6 km$^2$ for the case of a 20 m tunnel separation (which has been shown to be feasible based on extensive rock mechanics and thermal studies - OBAYASHI 1994).

---

$^1)$ Separation distance from the closest major water-conducting fault to ensure that the requirements on the geological safety barrier are met.
Fig. 4.1 Sketch of a possible repository layout; the case of 3 HLW emplacement panels on a single level and TRU silos in separate blocks of low-permeability basement between major (layout-determining) water-conducting faults
Even if smaller blocks are found at a particular site, the repository layout could be tailored to the available good rock by defining several emplacement panels (case shown in Fig. 4.1). For the case of distribution of the 120 GWa inventory over 3 panels, an average block area of ~0.3 km² would be required for a 20 m tunnel separation.

A single-level layout at a depth of ~1000 m below surface is implicitly assumed for the current performance assessment. Alternative designs involving stacked multiple-level emplacement layouts have also been considered (cf. Chapter 7). The reference design also assumes that silos for TRU are situated in a separate block, which would minimise the chance of direct interaction between these two waste types. The emplacement tunnels are overlain by at least 100 m of LPD basement, several hundred metres of HPD basement (~300 - 600 m) with the balance of the overburden being sedimentary formations.

4.2 The near-field

The key features of the near-field barriers are the large quantities of bentonite, steel and glass relative to the small quantity of radionuclides in the waste (Fig. 4.2, Tables 4.1 and 4.2) and the very low hydraulic conductivity of the bentonite, which ensures that solute transport in the near-field occurs predominantly by diffusion. The engineered barriers also comprise a chemically well buffered system, which will be relatively insensitive to changes in the surrounding geochemical environment.

The evolution of the near-field is expected to proceed as follows:

1) After emplacement, water will begin to resaturate any drained zones of the surrounding rock and then invade the bentonite, which will swell to seal any gaps present. At the same time, temperatures in the bentonite will increase due to radiogenic heat from the canister - maximum values being reached within a few tens of years (Fig. 4.3). Calculations indicate that complete resaturation may take in the order of hundreds of years.

2) The steel canister will consume any trapped oxygen relatively rapidly and will then corrode anaerobically. Anaerobic corrosion rates will be very low. The corrosion allowance of 5 cm thickness is designed to ensure a canister lifetime in excess of $10^3$ years. It is assumed that the canister eventually fails mechanically, due to the existence of internal void space.

3) The water chemistry in the near-field will be established by interactions of groundwater with the engineered barriers. The two most important materials by quantity are the bentonite (which will tend to buffer pH in the mildly alkaline region) and the steel canister (which will ensure that reducing conditions exist). The low groundwater fluxes and near-field temperatures generally below 100°C ensure that the bentonite itself will not undergo any significant mineralogical alteration over relevant timescales ($10^6$ years).
Fig. 4.2: Waste emplacement geometry (dimensions in metres)

Table 4.1: Material inventory in the near-field (per canister)

<table>
<thead>
<tr>
<th>Material</th>
<th>Volume ($m^3$)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>0.15</td>
<td>412</td>
</tr>
<tr>
<td>Steel fabrication container</td>
<td>0.01</td>
<td>75</td>
</tr>
<tr>
<td>Fabrication void</td>
<td>0.03</td>
<td>-</td>
</tr>
<tr>
<td>Canister*</td>
<td>1.2</td>
<td>8.4x10^3</td>
</tr>
<tr>
<td>Backfill</td>
<td>52.8</td>
<td>-</td>
</tr>
<tr>
<td>a) Bentonite (dry)</td>
<td>32.7</td>
<td>8.8x10^4</td>
</tr>
<tr>
<td>b) Pore space (water-filled)</td>
<td>20.1</td>
<td>2.0x10^4</td>
</tr>
</tbody>
</table>

*) including internal spacers, shielding etc.
**Fig. 4.3**: Example of results of thermal calculations showing the evolution of temperature on a radial profile from the centre of the waste glass to the host rock. This particular calculation is for a design variant which assumes a spacing between emplacement tunnels of 20 m (OBAYASHI 1994).

4) After canister failure, dissolution of the glass will occur in an environment with stagnant porewater. With a reference corrosion rate of \( \sim 3 \times 10^{-4} \text{ kg m}^{-2} \text{ a}^{-1} \), the glass will release contained radionuclides gradually over a period in the order of 10^5 years. The loss of many radionuclides from the immediate vicinity will, however, be further constrained by their low solubility limits (Table 4.3).

5) When radionuclides are released from the glass matrix, transport to the geosphere is greatly limited by the transport resistance of the bentonite backfill. Due to its extremely low hydraulic conductivity, solute transport through the saturated bentonite will occur predominantly by diffusion. Sorption processes (Table 4.3) result
in very low diffusivities for many radionuclides, so that their transport time through the backfill exceeds their half-lives and thus releases to the geosphere are negligible. Due to its microporous nature, compacted bentonite prevents significant migration of any colloids produced by corrosion of the waste matrix or the canister.

In reality, individual canisters will fail at different times and radionuclides will diffuse through remnant canister and the surrounding bentonite, with release into the nearest water-conducting features in the rock (Fig. 4.4a). In the conceptual near-field model for quantitative analysis, this system is simplified (Fig. 4.4b) by assuming:

a) All canisters fail at the same time.
b) After failure, the canister does not act as a transport barrier.
c) The corroding glass is represented as spherical beads in a water-filled reservoir.
d) Uniform conditions exist at the outer boundary of the bentonite.

In addition, spatial and temporal variations in the chemistry and transport properties of the near-field are ignored.

The total water flux through the repository depends very much on its layout in relation to surrounding major water-conducting faults, while its distribution depends on the distribution of water-conducting features within the low-permeability domain blocks. For the simplified near-field release model, however, only an average flux through the repository is required, which can be estimated from regional-scale average parameters (gradients and hydraulic conductivities). This leads to a calculated total flux through the repository of 3 m³ a⁻¹ but, due to the considerable uncertainties involved in its derivation, this parameter is varied widely in the sensitivity analysis.

4.3 The far-field

Apart from physically protecting the engineered barriers and providing an environment conducive to their longevity (low water flux, suitable groundwater chemistry), the geological barriers delay the release of any radionuclides which escape from the near-field and reduce their concentrations by dilution, dispersion and radioactive decay.

The components of the far-field (cf. Fig. 3.7) are:

1) The low-permeability domain of the crystalline basement, which is the repository host rock.
2) The higher-permeability domain of the crystalline basement.
3) Major water-conducting faults which penetrate the basement.
4) Overlying sedimentary formations.
5) The gravel aquifers in the groundwater discharge zone in the Rhine valley.
Table 4.2: Inventories of safety-relevant radionuclides and stable isotopes per waste canister, calculated for the reference canister failure time of 1000 years after waste emplacement

<table>
<thead>
<tr>
<th>Nuclides</th>
<th>Moles</th>
<th>Inventory</th>
<th>Half-life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Becquerels</td>
<td></td>
</tr>
<tr>
<td><strong>Single radionuclides and stable (stb) isotopes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni-stb</td>
<td>2.32x10^1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ni-59</td>
<td>1.07x10^-2</td>
<td>1.88x10^9</td>
<td>7.5x10^4</td>
</tr>
<tr>
<td>Se-stb</td>
<td>8.83x10^-1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Se-79</td>
<td>1.07x10^-1</td>
<td>2.18x10^10</td>
<td>6.5x10^4</td>
</tr>
<tr>
<td>Zr-93</td>
<td>1.06x10^1</td>
<td>9.20x10^10</td>
<td>1.53x10^6</td>
</tr>
<tr>
<td>Tc-99</td>
<td>1.04x10^1</td>
<td>6.48x10^11</td>
<td>2.13x10^5</td>
</tr>
<tr>
<td>Pd-stb</td>
<td>1.40x10^1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pd-107</td>
<td>2.56</td>
<td>5.20x10^9</td>
<td>6.5x10^6</td>
</tr>
<tr>
<td>Sn-stb</td>
<td>9.52x10^-1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sn-126</td>
<td>2.78x10^-1</td>
<td>3.67x10^10</td>
<td>1.0x10^5</td>
</tr>
<tr>
<td>Cs-135</td>
<td>3.30</td>
<td>1.90x10^10</td>
<td>2.3x10^6</td>
</tr>
<tr>
<td><strong>4n + 1 chain (neptunium chain)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cm-245</td>
<td>3.43x10^-3</td>
<td>5.33x10^9</td>
<td>8.5x10^3</td>
</tr>
<tr>
<td>Am-241</td>
<td>2.13x10^-1</td>
<td>6.51x10^12</td>
<td>4.32x10^2</td>
</tr>
<tr>
<td>Np-237</td>
<td>3.49</td>
<td>2.16x10^10</td>
<td>2.14x10^6</td>
</tr>
<tr>
<td>U-233</td>
<td>1.06x10^-3</td>
<td>8.84x10^7</td>
<td>1.59x10^5</td>
</tr>
<tr>
<td>Th-229</td>
<td>2.23x10^-6</td>
<td>4.01x10^6</td>
<td>7.34x10^3</td>
</tr>
<tr>
<td><strong>4n + 2 chain (uranium chain)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cm-246</td>
<td>3.38x10^-4</td>
<td>9.45x10^8</td>
<td>4.73x10^3</td>
</tr>
<tr>
<td>Pu-242</td>
<td>1.72x10^-2</td>
<td>6.04x10^8</td>
<td>3.76x10^5</td>
</tr>
<tr>
<td>U-238</td>
<td>8.11</td>
<td>2.40x10^7</td>
<td>4.47x10^9</td>
</tr>
<tr>
<td>U-234</td>
<td>1.11x10^-2</td>
<td>6.01x10^8</td>
<td>2.45x10^5</td>
</tr>
<tr>
<td>Th-230</td>
<td>4.58x10^-5</td>
<td>7.87x10^6</td>
<td>7.54x10^4</td>
</tr>
<tr>
<td>Ra-226</td>
<td>2.38x10^-7</td>
<td>1.97x10^6</td>
<td>1.60x10^3</td>
</tr>
<tr>
<td><strong>4n + 3 chain (plutonium chain)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Am-243</td>
<td>3.85x10^-1</td>
<td>6.90x10^11</td>
<td>7.38x10^3</td>
</tr>
<tr>
<td>Pu-239</td>
<td>2.52x10^-1</td>
<td>1.39x10^11</td>
<td>2.41x10^4</td>
</tr>
<tr>
<td>U-235</td>
<td>9.22x10^-2</td>
<td>1.73x10^6</td>
<td>7.04x10^8</td>
</tr>
<tr>
<td>Pa-231</td>
<td>2.10x10^-6</td>
<td>8.48x10^5</td>
<td>3.28x10^4</td>
</tr>
<tr>
<td><strong>4n + 4 chain (thorium chain)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pu-240</td>
<td>1.68x10^-1</td>
<td>3.40x10^11</td>
<td>6.54x10^3</td>
</tr>
<tr>
<td>U-236</td>
<td>5.82x10^-2</td>
<td>3.29x10^7</td>
<td>2.34x10^7</td>
</tr>
<tr>
<td>Th-232</td>
<td>4.89x10^-6</td>
<td>4.60</td>
<td>1.41x10^10</td>
</tr>
</tbody>
</table>
Table 4.3: Solubility limits for safety-relevant elements (derivation described in detail by BERNER (1994)) and sorption data for bentonite from STENHOUSE (1994)

<table>
<thead>
<tr>
<th>Element</th>
<th>Realistic</th>
<th>Conservative</th>
<th>Realistic</th>
<th>Conservative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Am</td>
<td>$10^{-5}$</td>
<td>$10^{-5}$</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>Cm</td>
<td>$6 \times 10^{-8}$</td>
<td>$10^{-5}$</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>Cs</td>
<td>high 4</td>
<td>high 4</td>
<td>0.01</td>
<td>0.001</td>
</tr>
<tr>
<td>Ni</td>
<td>high 4</td>
<td>high 4</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Np</td>
<td>$10^{-10}$</td>
<td>$10^{-8}$</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>Pa</td>
<td>$10^{-10}$</td>
<td>$10^{-7}$</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Pd</td>
<td>$\sim 10^{-11}$</td>
<td>$10^{-6}$</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Pu</td>
<td>$10^{-8}$</td>
<td>$10^{-6}$</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>Ra</td>
<td>$10^{-10}$</td>
<td>$10^{-10}$</td>
<td>0.01</td>
<td>0.001</td>
</tr>
<tr>
<td>Se</td>
<td>$10^{-8}$</td>
<td>$6 \times 10^{-7}$</td>
<td>0.005</td>
<td>0.001</td>
</tr>
<tr>
<td>Sn</td>
<td>$10^{-5}$</td>
<td>$10^{-5}$</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Tc</td>
<td>$10^{-7}$</td>
<td>high 4</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Th</td>
<td>$5 \times 10^{-9}$</td>
<td>$10^{-7}$</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>U</td>
<td>$10^{-7}$</td>
<td>$7 \times 10^{-5}$</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>Zr</td>
<td>$5 \times 10^{-9}$</td>
<td>$5 \times 10^{-7}$</td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

1) In the simplest case, it can be assumed that the ratio of the concentration of an element sorbed onto rock ($C_R$) to its concentration in solution ($C_W$) is a constant, i.e. $K_d = C_R/C_W$. For some real systems, empirical data are better described by a Freundlich isotherm: $\log (C_R) = \log \alpha + \beta \log (C_W)$; $\alpha$, $\beta$ constants.

3) "Realistic" data are termed "realistic-conservative" in the performance assessment because data are selected pessimistically to account for any uncertainties involved. "Conservative" datasets are even more pessimistic data values which represent a worst case for the particular process.

4) High indicates that the solubility is sufficiently large that saturation could significantly alter the porewater chemistry. For modelling purposes, this "unlimited" value could be set to an arbitrary value which is high enough not to be reached during performance assessment calculations (e.g. 10 M).
Fig. 4.4: The release of radionuclides from the near-field; (a) radionuclides will leach from the fractured glass matrix and diffuse through cracks in the canister and the bentonite backfill until they are incorporated into groundwater flowing in distinct water-conducting features. This is reduced to a much more simplified model (b) for quantitative analysis.
In the evaluation of radionuclide transport through the far-field, attention is focused on the low-permeability domain which provides the first and best characterised of the "geosphere" barriers. Siting can ensure that a minimum thickness of low-permeability crystalline (taken to be 100 m) surrounds the repository and must be traversed by any released radionuclides. Transport pathways through major water-conducting faults, higher-permeability domain and, possibly, overlying sedimentary aquifers are much less well defined and hence are not modelled directly. Similarly, dilution will occur along the flow path, as the relatively low fluxes of water from the low-permeability domain mix into much larger water flows, but this is difficult to quantify. Nevertheless, the net dilution of water passing through the repository during its transport to near-surface aquifers can be estimated by the contrast in water fluxes involved (e.g. dilution factor \( \times 10^6 \) for the case of outflow into a gravel aquifer).

On the basis of a regional analysis of groundwater chemistry, the predominant groundwater in the basement of the Area West is considered to be of the Na-SO\(_4\)-(Cl-HCO\(_3\)) type with about 1 g l\(^{-1}\) total dissolved solids. The major element composition of this reference water is given in Table 4.4.

Radionuclide transport through the host rock will occur predominantly in the distinct water-conducting features identified (cf. section 3.3) - namely a) cataclastic zones, b) jointed zones and c) fractured aplite/pegmatite dykes and aplitic gneisses.

The mineralogy and open (accessible to solute) porosity of the fracture infill materials and of the wallrock depend on the primary rock type and on the type of hydrothermal alteration or mineralisation which has taken place. However, mineralogy and porosity are largely independent of deformation type, i.e. no major distinctions have been found between cataclastic and jointed zones. While mineralogy and porosity may vary significantly on a small scale (range of dm - m), the variation is much less pronounced on a larger scale. Because geosphere transport of radionuclides from a repository will have a minimum path-length in the order of a hundred metres before reaching HPD or major water-conducting faults, it is justified to use average values for the whole LPD because local variations average out. In the dataset used for transport calculations, average mineralogical compositions and typical values for open porosities are given. The mineralogical database for these transport paths is used, in particular, to define their sorption properties. The extent of sorption of a particular radionuclide is a function of many parameters including water chemistry, the mineralogy of available surfaces and concentration of the sorbing species. For a defined reference water chemistry and temperature, sorption onto a rock is calculated as the sum of the contribution from the minerals present. The constant distribution coefficient (Kd) concept is applicable in cases where sorption can be taken to be fast, reversible and concentration-independent.

Although the sorption of many elements in natural rock/water systems is known to show some concentration dependence, of the key radionuclides for performance assessment, only Cs has been studied extensively enough to justify such sorption being represented by a Freundlich isotherm.
Table 4.4: Reference water chemistry for Area West (major components only)

<table>
<thead>
<tr>
<th>Component</th>
<th>Value (mg l⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.66</td>
</tr>
<tr>
<td>Eh (volts, from pe)</td>
<td>-0.18</td>
</tr>
<tr>
<td>Formation temp. (°C)</td>
<td>55</td>
</tr>
<tr>
<td>Lithium (Li⁺)</td>
<td>1.1</td>
</tr>
<tr>
<td>Sodium (Na⁺)</td>
<td>323.8</td>
</tr>
<tr>
<td>Potassium (K⁺)</td>
<td>8.5</td>
</tr>
<tr>
<td>Magnesium (Mg²⁺)</td>
<td>0.3</td>
</tr>
<tr>
<td>Calcium (Ca²⁺)</td>
<td>14.0</td>
</tr>
<tr>
<td>Strontium (Sr²⁺)</td>
<td>0.46</td>
</tr>
<tr>
<td>Fluoride (F⁻)</td>
<td>12.2</td>
</tr>
<tr>
<td>Chloride (Cl⁻)</td>
<td>128</td>
</tr>
<tr>
<td>Bromide (Br⁻)</td>
<td>0.72</td>
</tr>
<tr>
<td>Sulphate (SO₄²⁻)</td>
<td>296</td>
</tr>
<tr>
<td>Bicarbonate (HCO₃⁻)</td>
<td>285</td>
</tr>
<tr>
<td>Carbonate (CO₃²⁻)</td>
<td>2.7</td>
</tr>
<tr>
<td>Silica (H₂SiO₃)</td>
<td>46.1</td>
</tr>
<tr>
<td>Borate (B(OH)₃)</td>
<td>3.4</td>
</tr>
<tr>
<td>Total Iron</td>
<td>0.026</td>
</tr>
<tr>
<td>Organic Carbon</td>
<td>0.04</td>
</tr>
</tbody>
</table>

At the level of uncertainty involved, however, a single sorption database was considered to adequately represent fracture infill and altered wallrock for all 3 water-conducting features (Table 4.5).

For radionuclide transport modelling, a detailed description of the small-scale geometry of the features in which flow occurs and the rock surfaces that are encountered is essential. The detailed descriptions derived from field observations of these features were simplified to define model systems (Fig. 4.5). For each, groundwater flow occurs in only a small fraction of the total volume of these planar features - observed as open channels. Such channels are separated by zones in which fractures are sealed with infill; in reality such infill may be permeable but, in the geosphere model, advection through such material is considered to be negligible relative to that in the channels. The processes that caused fracturing of the rock and rock/water interaction during the subsequent flow of hydrothermal waters through such fractures resulted in the formation of an alteration zone immediately surrounding the fracture (indicated in Fig. 4.5). For the idealised planar fractures, the alteration zone is represented by a uniform layer of defined thickness. Beyond this layer, the rock is considered to be unaltered. Solute penetration into fracture infill and altered wallrock occurs by diffusion. Apart from the geometry of the water-conducting features, important rock properties needed to characterise diffusion are the connected
porosity of the rock involved, the diffusivity of solute in this porosity (a function of the tortuosity and constrictivity of the pores involved), the extent of radionuclide sorption onto pore surfaces and the extent to which such connected porosity extends into the bulk rock.

It is generally assumed that all far-field solute transport occurs in pure solution. Colloid concentrations have been studied in several deep groundwaters in the crystalline rocks and found to range from 7 to 400 \( \mu \text{g} \text{l}^{-1} \), with expected concentration in the reference water of <100 \( \mu \text{g} \text{l}^{-1} \). These colloids consist predominantly of clays and silica. Calculations have thus been performed assuming a colloid population of 100 \( \mu \text{g} \text{l}^{-1} \) characterised by a high sorption coefficient \( (10^4 \text{m}^3 \text{kg}^{-1}) \). A model assumption is that colloids do not interact with flow path walls or diffuse into the rock matrix. It has been assumed that colloids are advected with the mean flow velocity of groundwater in the flow path.

Table 4.5: Kristallin-I geosphere sorption \((K_d)\) database for safety-relevant elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Realistic ((\text{m}^3 \text{kg}^{-1}))</th>
<th>Conservative ((\text{m}^3 \text{kg}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Am</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Cm</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>Cs*</td>
<td>0.042</td>
<td>0.0084</td>
</tr>
<tr>
<td>Ni</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Np</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>Pa</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Pd</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Pu</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>Ra</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Se</td>
<td>0.01</td>
<td>0.001</td>
</tr>
<tr>
<td>Sn</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Tc</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Th</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>U</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>Zr</td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

*) Value derived from Freundlich isotherms specified (reference footnote 2 in Table 4.3)
Figure 4.5: Example of a small-scale conceptual model of a water-conducting feature identified in the crystalline basement of Switzerland (cataclastic zone) (unlabelled).
4.4 The biosphere

No releases of radionuclides from the repository to the biosphere are expected within the first thousand years after repository closure and maximum releases might well occur hundreds of thousands of years in the future. It is clearly impossible to predict the evolution of either the surface environment or of human culture over such timescales and this fact is explicitly recognised in the Swiss regulatory guidelines (HSK & KSA 1993). As recommended by these guidelines, reference biospheres are defined based on current living habits and present-day climate, geography etc. in expected exfiltration areas, although potential long-term changes in these conditions are also examined.

The region where the release of groundwater-transported radionuclides from the Kristallin-I repository occurs broadly corresponds to the northern border of present-day Switzerland, defined by the Rhine valley. The topography is characterised by relatively gently sloping valley bottoms formed on the gravels laid down in the Quaternary period, with higher elevations to the north and the south. The Rhine forms the major drainage feature for groundwater in the region and also the main transport path for radionuclides in the surface environment out of the system.

The gravels of the Rhine river valley, where discharge is expected to occur, carry a broad groundwater stream, which is locally in contact with the crystalline basement or the overlying sediments.

Volumetric flows in this aquifer range from $\sim 10^6$ m$^3$ a$^{-1}$ to $\sim 10^7$ m$^3$ a$^{-1}$. For comparison it may be noted that the average volumetric flow in the Rhine river is in the order of $10^{10}$ m$^3$ a$^{-1}$.

The climate of the region is temperate and shows little spatial variation along the section of the Rhine valley of interest in this study. The mean annual temperature is 8-12°C and annual mean rainfall is about 800 mm a$^{-1}$. Evapotranspiration accounts for around one third of the precipitation. Natural vegetation is almost entirely absent from the region. The present landscape is the cumulative result of human cultivation over the past few thousand years.

5) "...dose calculations for the distant future are not to be interpreted as effective predictions of radiation exposures of a defined population group. They are, in fact, much more in the nature of indicators for evaluating the impact of a potential release of radionuclides into the biosphere."
In order to provide conservative overestimates of radionuclide uptake, the human lifestyle modelled is that of subsistence agriculture, as has been practised in the area of interest until comparatively recent times. The present-day population density is 50-500 persons km$^{-2}$. Agriculture is very important to the regional economy. This includes animal husbandry and arable farming as well as forestry (mainly conifer plantations). Between 15 to 45% of the open agricultural land is devoted to vegetable and fruit production, with the remainder being used for livestock grazing (pasture land) or for growing animal foodstuffs (maize, root crops, etc.).

Historical records show extensive use of the near-surface aquifers in the gravel of the valley bottoms. This is of importance for the form of the subsistence agriculture biosphere model employed in the performance assessment. Additionally, there are several extraction sites, with pumping rates up to 5,000 litres min$^{-1}$ in the region, as well as a number of mineral water sources and hot spas. The water from these latter sources has deeper origins (e.g. the higher-permeability domain).

The geographic and hydrogeological information is simplified in the form of a compartment model which allows fluxes of radionuclides between various components of the biosphere to be assessed (Fig. 4.6). This provides the input for a food-chain model which is used to calculate the accumulation of radionuclides in various foodstuffs, as well as the resultant radiation dose from ingestion, inhalation and external exposure.
Fig. 4.6: General arrangement of the principal compartments in the biosphere. The Elsewhere compartment acts as a sink to represent all losses from the geographical area examined.
5 PERFORMANCE ASSESSMENT: APPROACH AND ANALYTICAL METHODS

5.1 Introduction

In the Kristallin-I performance assessment, the basic understanding of the repository system in its geological environment is analysed in a formal manner to identify possible paths of future evolution in a process called scenario development. Scenarios which require quantitative treatment are selected and analysed using various mathematical models which are treated using computer codes. This Chapter outlines the process of scenario development and the analytical methods used for quantitative analysis of specific scenarios and discusses the verification and validation of such mathematical models and codes along with their associated databases.

5.2 Scenario development

5.2.1 Background and terminology

A particular feature of the performance assessment of geological disposal of radioactive waste is the very long timescale over which assurance of safety is sought (in the order of a million years or so). Over such timescales, both the natural environment and the engineered structures will change considerably. There will be large and unavoidable uncertainty about the future state or evolution of the system due to:

- Uncertainty about the importance or rate of various natural processes which will act on the system.
- Lack of knowledge about the timing or frequency of certain natural phenomena.
- Uncertainty about human activities in the far future, e.g. groundwater and mineral resource use.

The consequent uncertainty in future conditions is handled by carrying out performance assessment calculations for a number of simplified or stylised conceptual descriptions of future state or evolution, termed scenarios. The SKI, HSK, SSI Working Group on regulatory guidance (SKI, HSK, SSI 1990) described scenarios as:

"...future evolutions........, each of them being a hypothetical, but physically possible, sequence of processes and events that influence the release and transport of radionuclides from the repository to the biosphere and the exposure to humans. The set of scenarios defined for a particular repository and which will be considered in the performance assessment should form an envelope within which the future evolution of the repository system is expected to lie."

Scenarios need not necessarily be particularly realistic; simplified scenarios that are selected for analysis often incorporate features or assumptions that are very unrealistic, e.g. constant environmental conditions over time periods in which natural
geomorphological and/or ecological changes operate. The most important aspect to stress is that scenarios should form a set covering the expected range of possible future conditions and evolutions.

5.2.2 The scenario development procedure

The procedure used includes the following broad stages:

1) Documentation of understanding of the system and processes relevant to its behaviour.

2) Development of a catalogue of all potentially relevant features, events and processes (FEPs).

3) Specification of the system concept - a description of the behaviour of the repository system indicating the interactions of all relevant FEPs.

4) Development of the safety assessment concept - a conceptual model of all FEPs to be taken into account in assessment calculations.

5) Development of the robust safety assessment concept - incorporating all detrimental FEPs but including only well understood FEPs which contribute to safety.

To assess overall system behaviour detailed models of key processes are utilised which attempt to be realistic; best-estimate calculations are made and parametric sensitivity analysis is used to explore the uncertainty associated with important phenomena. To assess safety-relevant behaviour, models are used which may be somewhat simpler; these may be calibrated against the more realistic models or adopt parameters that are derived through more detailed analyses. Finally, a robust safety analysis is obtained which, even if rather unrealistic, should lead to calculation of results which are defendably conservative (Fig. 5.1).

The process of reduction and/or simplification cannot reduce the inherent uncertainty in system behaviour, rather the uncertainty is replaced by pessimism, or conservatism, e.g. processes which may aid safety but cannot be relied on are not taken into account and parameter values are selected conservatively. The objective is to provide estimates of bounding behaviour which have a high associated level of confidence.

Screening arguments define the scope of the assessment in broad terms. In the Nagra scenario development procedure, two groups of screening arguments are used:

1) Site and disposal concept constraints - these allow phenomena that are physically impossible or irrelevant for the given site and disposal concept to be screened out.

2) Assessment basis or "ground rules" constraints - these define the scope of the safety assessment and thus allow phenomena outwith that scope to be screened out.
Table 5.1 lists titles of screening arguments used in a preliminary scenario development. The procedures used to compile and audit the FEP list are fully documented (SUMERLING & GROGAN 1994).

Table 5.1: Titles of screening arguments and examples of FEPs screened out by them

<table>
<thead>
<tr>
<th>Screening arguments</th>
<th>Examples of FEPs screened out</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 Site and disposal concept</strong></td>
<td></td>
</tr>
<tr>
<td>1.1 Waste-form and packaging</td>
<td>Other waste type FEPs, Cu canister FEPs</td>
</tr>
<tr>
<td>1.2 Waste emplacement and repository</td>
<td>Cementitious backfill FEPs</td>
</tr>
<tr>
<td>1.3 Host geology (crystalline basement)</td>
<td>Salt diapirism</td>
</tr>
<tr>
<td>1.4 Local and regional surface environment</td>
<td>Estuarine and marine FEPs</td>
</tr>
<tr>
<td>1.5 Geographical location</td>
<td>Sea level rise/fall etc.</td>
</tr>
<tr>
<td><strong>2 Assessment basis</strong></td>
<td></td>
</tr>
<tr>
<td>2.1 Appropriate repository design and closure</td>
<td>Repository left unsealed</td>
</tr>
<tr>
<td>2.2 No consideration of global and regional disasters</td>
<td>Nuclear war</td>
</tr>
<tr>
<td>2.3 No consideration of malicious acts</td>
<td>Terrorism</td>
</tr>
<tr>
<td>2.4 No consideration of deliberate intrusion</td>
<td>Recovery of wastes</td>
</tr>
<tr>
<td>2.5 No consideration of future human society and technology</td>
<td>Futuristic technologies, cure for cancer</td>
</tr>
<tr>
<td>2.6 Limitation to post-closure radiological assessment</td>
<td>Non-radiological impacts</td>
</tr>
<tr>
<td>2.7 No consideration of future life evolution</td>
<td>Changed radio-sensitivity of man</td>
</tr>
</tbody>
</table>
Taking one main safety-relevant feature at a time (e.g. the glass, canister, buffer, etc.), all the FEPs relevant to it are examined in order to define the system concept. Links between the FEPs are noted and an influence diagram is built up which records these relationships. The safety assessment concept is defined by simplification of the system concept influence diagrams. For example, several different processes may be involved in the corrosion of steel but, in the safety assessment, corrosion may be represented by a global corrosion rate or simply by a failure of containment at a given time.

The above procedure leads to definition of the Reference Scenario. In this scenario, it is assumed that the siting of the repository in a stable, deep geological formation isolates the system from significant variations due to natural surface environment processes, human activities and geological events and processes, and that the engineered barriers behave as designed. The present-day hydrogeological regime, surface hydrology, morphology and climate are assumed, plus a subsistence agricultural community living in the exfiltration zone.

The Reference Scenario is expected to include all the phenomena most relevant to the long-term radiological performance of the system, with the exception of some beneficial phenomena which are deliberately excluded, e.g. because of uncertainty (limited confidence) in the appropriateness of models and data to represent the phenomena. These phenomena are termed "reserve" FEPs (Table 5.2). Within the Reference Scenario, a range of alternative conceptual models is identified for key phenomena. Where equally likely alternatives are identified for components of the disposal system, the model leading to the highest consequences is incorporated in the Reference Model Assumptions. A conservative approach is also used in deriving a set of Reference Parameters; these are termed "realistic-conservative" values.

The combination of the Reference Scenario, Reference Model Assumptions and Reference Parameters (Fig. 5.2) is termed the "Reference Case". Sensitivity to parameter uncertainty within the Reference Scenario and Reference Model Assumptions is examined by varying individual parameter values, typically in a pessimistic sense, to account for maximum likely variations. The impact of alternative model assumptions within the Reference Scenario is also examined, as are the potential impacts of several alternative scenarios.

In addition to this, an even more conservative set of calculations - the Robust Scenario, based on a set of Robust Assessment Model Assumptions - is made. In this scenario credit is taken only for those parts of the safety system in which high confidence can be placed; for example, the problems of characterising the host rock over large distances leads to the neglect of all, potentially very important retardation effects in the geosphere. This provides results which are confidently expected to overestimate the radiological impact.
Table 5.2: Examples of reserve FEPs

<table>
<thead>
<tr>
<th>Barrier</th>
<th>Reserve FEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass matrix</td>
<td>Incorporation of radionuclides into corrosion products</td>
</tr>
<tr>
<td>Steel canister</td>
<td>Radionuclide sorption onto/coprecipitation with corrosion products</td>
</tr>
<tr>
<td>Bentonite</td>
<td>Radionuclide transport into backfill between canisters</td>
</tr>
<tr>
<td>Geosphere</td>
<td>Radionuclide retardation in major water-conducting faults and HPD basement</td>
</tr>
</tbody>
</table>

5.3 Quantitative analysis

The quantitative analysis is based on a hierarchy of scenarios, model assumptions and parameters summarised in Fig. 5.2. For each of these, the scenario description lists all the FEPs considered and also notes the particular assumptions and simplifications involved in representing the scenario by a particular model.

Fig. 5.2: Outline of the structure of the quantitative assessment for Kristallin-I. The combination of Reference Scenario, Model Assumptions and Parameters, indicated by the heavy line, is termed the Reference Case.
The key PEPs considered in the Reference Case are summarised in Fig. 5.3. The calculations required are carried out with the Nagra assessment model chain (Fig. 5.4). In Kristallin-I, three codes are included in this chain - STRENG (radionuclide release and transport in the near-field), RANCHMD (radionuclide migration in the geosphere) and TAME (radionuclide distribution through the biosphere, uptake in the food-chain and dose to man). For cases using this model chain, a formalised system of nomenclature of input and output files was adopted for quality assurance purposes.

The basic performance assessment models are supported by a series of other models and analyses which define the boundary conditions and databases used and support model assumptions. For example, the thermal calculations described previously are used to support the implicit STRENG model assumption of a homogeneous temperature field at about rock ambient values after canister failure (at reference time of 1000 years).

The STRENG code is used to model the dissolution of borosilicate glass subsequent to canister failure and the congruent release of contained radionuclides, constrained by solubility limits and their diffusion through the bentonite backfill. Explicit representation of diffusion for all radionuclides represents an improvement in the near-field model since the PG’85 analysis.

The model is based on the assumptions that:

1) At the time of canister failure, the bentonite is fully saturated, homogeneous in its physical and chemical properties and effectively isothermal at about rock ambient temperature.

2) Glass dissolution can be defined as a function of glass surface area and is otherwise independent of time.

3) Elemental solubility limits can be defined which are constant with time and can be partitioned between isotopes in relation to their relative abundance (stable isotope supply from bentonite porewater or canister corrosion are not considered).

4) The failed canister presents no barrier to solute transport.

5) Solute sorption in compacted bentonite can be represented by a simple distribution constant.

Geometry is simplified by representing transport in the bentonite backfill as one-dimensional radial diffusion. Radioactive decay and ingrowth are handled for individual nuclides and decay chains.
Main safety relevant features:

**ENGINEERED BARRIERS**
- GLASS
- STEEL CANISTER
- BENTONITE BUFFER

**CRYSTALLINE BASEMENT**
- BUFFER/ HOST ROCK INTERFACE
- LPD
- HPD & MWCFs
- BIOSPHERE

Key environmental properties and processes:
- Glass dissolution
- Congruent release of RNs to porewater
- Oxic and anoxic corrosion
- Mechanical failure at 1000 years after emplacement
- Very low permeability, stable chemistry, colloid transport excluded
- Resaturation of excavation disturbed zone (EDZ)
- Water flow through repository zone, transport in open fractures
- Slow water flow in water-conducting features (WCFs)

Key radionuclide release and transport processes and assumptions:
- Elemental solubility limits aqueous concentration of many RNs
- Physical effect of failed canister neglected
- Radial diffusion thru' buffer with sorption
- Immediate transport to a water-conducting feature
- Slow advection with diffusion to stagnant pores and sorption
- Immediate transport to biosphere

**DOSE TO MAN**

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Fig. 5.3: Overview of the Reference Case. For each of the system components (upper boxes), features and events are defined (rectangular boxes), which provide the constraints on the processes which are quantitatively modelled (rounded boxes) or explicitly neglected if this can be shown to be conservative (reserve FEP).
Fig. 5.4: The Nagra assessment model chain (codes STRENG, RANCHMD and TAME) and supporting models
The complexity of groundwater flow and radionuclide transport at the repository tunnel wall (which is dependent on the extent of an excavation disturbed zone and its hydraulic properties) is represented by two different external boundary conditions:

a) A mixing tank boundary (Reference Model Assumption - cf. Fig. 4.4) in which the external concentration at the interface is set so that the diffusive flux from the bentonite equals the advective removal rate.

b) A zero concentration outer boundary which, although unrealistic, will over-predict diffusive releases.

The RANCHMD code models advective transport of radionuclides released from the near-field through water-conducting features of the geosphere. The basic code is unaltered from that used in PG'85 (HADERMANN & RÖSEL 1985).

Since PG'85, however, considerable effort has gone into defining the geometry of the openings within water-conducting features in the crystalline basement (cf. section 4.3). The model representation of such conduits - in which all groundwater flow is assumed to occur - is further simplified in RANCHMD as either continuous cylindrical tubes or parallel plate fractures (Fig. 5.5). The geometric simplification involved for the 3 distinct water-conducting features is indicated in Fig. 5.6.

The processes included directly within the RANCHMD code are:

- Groundwater flow in vugs with a constant velocity.
- Solute diffusion normal to the direction of flow into the surrounding rock matrix.
- Reversible sorption of radionuclides onto pore surfaces.
- Hydrodynamic dispersion.

Model parameters (velocity, sorption and diffusion coefficients, etc.) are considered to be constant in space and time. The extent to which the porosity of the rock matrix is connected to the channels in which groundwater flow occurs is an important parameter which is not well defined. As indicated in Fig. 5.6, alternatives of the connected porosity being limited to a narrow zone around the water-carrying channel and of all wall rock within the water-conducting feature containing connected porosity are considered.

Although the basic code considers only "Kd" type sorption (see section 4.3), a variant, RANCHMDNL, allows sorption to be represented by a Freundlich isotherm (defined only for Cs). Transformation of the input parameters also allows the RANCHMD code to represent radionuclide transport by colloids. A Reference Model Assumption is that only transport through the low-permeability domain is directly considered (i.e. no retardation/decay in other parts of the flow path to the surface). As a variation, transport in a major water-conducting fault is also assessed.
Fig. 5.5: Schematic representation of the geosphere transport model. Advection/dispersion are modelled with either: a) a parallel-walled conduit, "planar geometry", or b) a tubular conduit, "cylindrical geometry". Diffusion into a porous matrix is also considered in both cases.
Fig. 5.6: Simplification of the water-conducting features identified in the crystalline basement for representation in the geosphere transport model. The option in bold script corresponds to the Reference Model Assumption included in the Reference Case.

The TAME (Terrestrial-Aquatic Model of the Environment) code quantifies the transport of radionuclides in the biosphere and their uptake and accumulation in exposure pathways. It consists of two distinct parts: a compartment model for the calculation of the time evolution of the radionuclide inventories in the elements of the biosphere system (cf. Fig. 4.6) and an exposure pathway model for estimation of the doses received by individual inhabitants in the region of interest. At the heart of TAME are transfer coefficients which determine fractional transfer rates of contaminants between environmental compartments. These transfer coefficients are derived using site-specific environmental data. Doses as a function of time are calculated using present-day data for human behaviour, environmental factors, and inventories derived from the compartment model.
Two major exfiltration scenarios have been identified:

- The present-day situation, with the Rhine valley filled with gravel sediments (Reference Scenario).
- A situation where the gravels have been removed by erosion and the bed of the Rhine is on the upper crystalline basement.

A further exfiltration scenario considered is the release of radionuclides into a gravel aquifer near a small tributary of the Rhine, rather than to the main part of the valley.

The case of direct extraction of deep groundwater via a well is considered in a further scenario which focuses on its use as a supply of drinking-water.

Alternative climate states and, particularly, their influence on near-surface hydrogeology and agricultural practices (e.g. extent of irrigation) have also been considered:

- A dry climate, with greatly reduced precipitation and increased evapotranspiration as compared with the present-day.
- A humid climate, with increased rainfall and evapotranspiration.
- A cold climate (tundra) in which there is no flow of water between the geosphere and the river and soils because of permafrost. The human lifestyle in this biosphere is predominantly based on the lichen-reindeer pathway.

5.4 Verification and validation of models and their associated databases

Because of the multi-disciplinary nature of performance assessment and its use of "state-of-the-art" research tools special attention has to be devoted to quality assurance/quality control (QA/QC). In Kristallin-I, a number of procedures were used to ensure that the quality of the conclusions of this assessment could be defended:

- A formal scenario analysis, to ensure transparency and traceability of the processes of defining the calculations to be carried out.
- A rigorous system of nomenclature which allows the calculated output data/figures to be unambiguously traced to the corresponding input.
- Verification of computer codes.
- Validation of models and associated databases.
- Technical peer review of documentation.

The scenario analysis methodology was outlined in section 5.2. Full documentation of the procedures used to derive a comprehensive FEP list, to screen these FEPs and to organise them into scenarios allows the basis for all assessment evaluations carried out (either quantitative or qualitative) to be traced (SUMERLING & GROGAN 1994). In addition, the catalogue of relevant FEPs includes a summary of current understanding of each one, along with key references to the literature supporting both concepts and
numerical data. This catalogue has been extensively reviewed both internally and externally.

Every calculation using the performance assessment model chain is assigned a unique name which can be directly related to the models used, along with associated databases (NAGRA 1994; Appendices 3 & 4). This name is automatically printed with all data files and associated tabular or graphical output, along with information of the version numbers of the codes used. All calculations are thus both traceable and reproducible.

The computer codes and associated databases used in the assessment calculations are tested to ensure that they correctly solve the governing equations used to model a particular system (verification). Verification is a fundamental part of code development and includes, in particular, comparison with analytical solutions for simple test cases. More complex test cases can be examined by intercomparison of independent codes; this has been done for many codes used in Kristallin-I, generally as part of international collaboration exercises.

A more challenging process is the demonstration that a conceptual model, along with its associated computer code/database, adequately represents the real system examined. Much of the controversy in this area arises from alternative interpretations of the term "validation" which range from an inherently unachievable "proof of truth" (e.g. BREDEHOEFT & KONIKOW 1993) to a more pragmatic emphasis on the subjective aspect of assessing if a model is "good enough" (e.g. McCOMBIE & McKinley 1993). The requirement for validation is included in Swiss regulations, where it is defined as "Providing confidence that a computer code used in safety analysis is applicable for the specific repository system" (HSK & KSA 1993). Using this definition, a case has been made to demonstrate the applicability of all models used either directly in the assessment model chain, or indirectly to provide input data or to specify boundary conditions. For individual models, this involves discussion of the degree of understanding of the process (or processes) modelled and comparison of model output with laboratory, field or natural analogue observations. A very good example here is the testing of the conceptual model for radionuclide transport in the Migration Experiment at the Grimsel Test Site (FRICK et al. 1992). Evaluation of the adequacy of each model includes a subjective component which involves consideration of how critical the model is to the overall demonstration of safety. In addition to testing of the individual models used in performance assessment, the assessment as a whole can be evaluated by comparison of databases and results with similar assessments (e.g. the Japanese H-3 analysis or the Swedish SKB91 study, NEALL 1994).

The final stage of quality assurance involves technical reviews of documentation (including, where appropriate, checking databases and calculations) by both internal and external experts. Technical reports in the Nagra NTB series (including the Kristallin-I summary reports) are submitted for independent review in a process which has been formalised in QA/QC guidelines. Additionally, many of the key studies supporting Kristallin-I have been reported in peer-reviewed journals.
6 PERFORMANCE ASSESSMENT RESULTS AND THEIR INTERPRETATION

6.1 Presentation of model results

This Chapter focuses on the presentation and discussion of the results of the performance assessment. It should be emphasised that the models used are a simplification of the repository system and are not intended to predict its evolution as it will occur in reality. Rather, the scenario analysis specifies possible courses of future evolution which provide the basis for a set of mathematical calculations. The models used simulate the performance of the system in a conservative manner - tending to over-predict consequences in terms of releases or doses.

The modelling process frequently involves extensive extrapolations of data or assumptions over wide ranges and care must be taken to determine when the justification of such extrapolations begins to break down. This is particularly true for the case of extrapolations over long time periods, when slow geological processes will have changed the environment sufficiently that the present-day geological database is no longer valid. The Kristallin-I concept of deep disposal in crystalline rocks overlain by sediments ensures that the near-field environment changes only very slowly with time. Taken together with the hydraulic and chemical buffering provided by the bentonite backfill, it is reasonable to assume that the basic near-field model will be valid for timescales in the order of a million years - by which time the toxicity of the waste will have decreased to very low levels.

The repository will be sufficiently deep to be little influenced by surface processes such as climate alteration or erosion. Rock movements expected due to tectonic evolution would be concentrated along existing zones of weakness and are not anticipated to alter greatly water fluxes, water-conducting feature properties or geochemistry on a million-year timescale.

Shallower crystalline rock units, the overlying sediments and the biosphere will, however, be significantly altered over much shorter periods, in particular due to changes associated with future glaciation (expected within $\sim 10^4$ a). The biosphere model is, indeed, susceptible to even shorter term alterations of human behaviour - which can change dramatically on a timescale of decades or centuries. The use of the biosphere model to convert releases of radionuclides into resultant doses must thus be regarded as illustrative only. A wide range of altered evolution biosphere scenarios are considered in order to indicate the types of uncertainties which may be involved with such conversions.

To remind the reader of these uncertainties, a system of shading has been introduced for graphs presenting calculated doses (cf. Fig. 6.1). On the time axis, periods up to $10^4$ a are unshaded, representing the period of time for which extrapolation of performance of the engineered barriers is reasonably assured and the models can be well supported by natural analogue considerations. The period from $10^4$ to $10^6$ a is lightly shaded to indicate that the basic models of radionuclide release and transport
are considered to be valid over this period, but parameter values must be considered to become increasingly uncertain at times at the upper end of this range. Beyond $10^6 \text{a}$ a darker shading is used to indicate that here even the applicability of all components of the model chain is uncertain. Results are presented to $10^7 \text{a}$ but these can only be considered as a qualitative indication of trends.

As emphasised above, the conversion of released radionuclide fluxes into doses should be considered as illustrative only. To put the numbers in context, however, the regulatory guideline is indicated on all plots, generally along with a band representing the natural background radiation exposure in Switzerland. Shading is also introduced for doses less than $10^{-7} \text{mSv a}^{-1}$ - a level which can be considered negligible (two orders of magnitude below that resulting from drinking one glass of average Swiss mineral water per year). In fact, doses below about $10^{-2} \text{mSv a}^{-1}$ can be considered to have little real significance for individual health (NEALL 1994, cf. also Fig. 6.6), but much lower cut-offs must be used in order to illustrate trends of model results as, otherwise, most plots of results would be blank.

### 6.2 The results of the Reference Case analysis

In the Reference Case, all canisters fail simultaneously after their minimum design lifetime, by which time the near-field will be effectively isothermal at the host rock ambient temperature. Corrosion of the borosilicate glass waste-form is taken to proceed congruently and releases of particular radionuclides to be constrained by their low solubility in the reducing, slightly alkaline porewaters of the near-field.

Radionuclides slowly diffuse through the backfill at a rate constrained by element-specific retardation processes and are released into flowing groundwater. The repository is assumed to be situated in the sitting Area West. Transport through the low-permeability domain is represented by a 200 m flow path through a representative water-conducting feature. This particular representation minimises the barrier role of the geosphere.

By assuming that releases occur into the Rhine gravels in an area inhabited by a subsistence farming community, and taking climatic and human behaviour data typical of the present-day, the doses resulting from releases from the repository can be calculated (Fig. 6.1a).

An obvious conclusion is that calculated consequences of radionuclide releases are very low - the maximum dose is more than 2 orders of magnitude below the regulatory guideline and 3-4 orders of magnitude below the natural radiation background.

Releases also occur only in the distant future; no significant releases to the biosphere are predicted for the first $10^4 \text{a}$, which is about the time that the next period of glaciation is expected (and is also the time at which quantitative analysis is currently terminated in some countries, such as the USA). The peak release, due predominantly to the long-lived fission product Cs-135, occurs after $10^5 \text{a}$. The long-lived actinides and their daughters would not be released within $10^6 \text{a}$. 

The relative roles of the near- and far-field can be indicated by evaluating the hypothetical case where the geosphere barrier is short-circuited and releases from the engineered barriers pass directly into the biosphere (Fig. 6.1b). Although physically unreasonable, this representation illustrates that the near-field is extremely effective and, even without the geosphere transport barrier, ensures that releases are well below safety guidelines. In this respect, it can be seen that the critical role of the host rock in the Kristallin-I analysis is to physically protect the engineered barriers and to ensure their longevity. By comparing parts a) and b) of Fig. 6.1 it can be seen that the geosphere clearly delays breakthrough of releases for $\sim 10^4$ a and very significantly reduces concentrations of some shorter-lived radionuclides (e.g. Sn-126, Tc-99).

6.3 Parameter variations and alternative model assumptions within the Reference Scenario

The Reference Case described above serves as a standard against which to determine the sensitivity of results to parameter uncertainties or changes in the model assumptions used. In this section, calculations performed within the framework of the Reference Scenario are discussed, while alternative scenarios are considered in section 6.4.

6.3.1 Parameter variations

Near-field
The key parameters which determine near-field performance in the Reference Case are:

- Canister lifetime
- Glass corrosion rate
- Elemental solubilities
- Elemental sorption on bentonite
- Groundwater flux around the engineered barriers

These are now considered in turn, emphasising the effects of selecting more conservative values.

The canister lifetime (in terms of loss of containment) of $10^3$ a is considered to be very conservative with respect to the assumed corrosion rate. Failure in less than several hundred years is considered extremely unlikely but, even then, would have little significant effect on releases due to the constraints set by the slow dissolution rate of the glass waste-form and the powerful barrier role played by the bentonite. Even less likely is the case of failure soon after emplacement (within 100 a, say), but this would not be expected to increase doses significantly, although the applicability of the model could be questioned due, for example, to the higher temperatures which are present.
Natural radiation exposures in Switzerland

Regulatory Guideline: 0.1 mSv a⁻¹

(a) Reference Case

(b) Reference Case biosphere, direct release to the biosphere (no geosphere)

Key to radionuclides.
- Sum over nuclides.
- 4N + 1 chain
- 4N + 3 chain
- 4N + 2 chain
- 133Cs
- 59Ni
- 99Tc
- 125Sn
- 79Se
- 93Zr

Fig. 6.1: Time development of the annual individual doses in the Reference Case
a) Results of the Reference Case calculations, b) as an illustration of the effect of the geosphere as a barrier, the hypothetical case of direct release of radionuclides from the near-field to the biosphere is also presented.
The model would, however, probably tend to be conservative at such times as the inner zone of the bentonite would still be in the process of resaturation. The waste-form would thus not be exposed to liquid water and, in addition, a net flux of water towards the canister would be expected to prevent radionuclide transport.

The glass corrosion rate chosen was based on an extrapolation of laboratory experiments and is believed to be reasonably conservative but calculations were repeated assuming a value 2 orders of magnitude higher. The release rates of most radionuclides are unaffected by this change as their release rate is, in any case, constrained by their low solubilities. A notable exception is Cs-135 which is not solubility-limited. The maximum Cs-135 release concentration from the near-field does not scale linearly with the glass corrosion rate, however, due to "spreading of the peak" during transport through the bentonite, which means that the increase in resultant dose is only by less than one order of magnitude. Calculated doses are, therefore, still well below the regulatory guidelines.

Elemental solubility limits are a very important constraint on the releases of many radionuclides and selecting a set of more conservative values of this parameter significantly alters the profile of calculated doses as a function of time. Decay during near-field and geosphere transport minimises the consequences of such changes for some nuclides as does the fact that, as solubilities increase, glass corrosion rates take over as a constraint on releases.

There is a fairly large body of experimental data to support selection of "realistic" elemental diffusivities (derived from the bentonite sorption database) for the bentonite backfill. Repeating the calculations with more conservative sorption distribution coefficients (generally a factor of 10 smaller) has little effect on calculated releases from the geosphere, even though the near-field release profiles change somewhat. A major effect of such increased diffusivity is to allow release from the bentonite of some isotopes which otherwise decay within the near-field (Ni-59, Sn-126, Pu-239, Pu-242). However, these radionuclides are not dominant contributors to dose and, in any case, will decay within the far-field.

The rate of diffusion through the backfill is influenced by the rate at which dissolved species can be removed from its outer surface which is related, in turn, to the water flux around the engineered barriers. The sensitivity of releases to this parameter was evaluated by repeating calculations assuming fluxes one or two orders of magnitude higher than in the Reference Case. In fact, increased water flux simultaneously influences transport in the geosphere and the net effect of this parameter variation is considered in the following section. Nevertheless, considering the near-field only, calculations show that increasing the flux by a factor of 100 causes an increase of the maximum release rate of Cs-135 by a factor of only about 5, although the maximum is reached at an earlier time (~10^4 a rather than ~10^5 a). Increasing the flux has a more dramatic effect on releases of other radionuclides. For example, the release rate of Se-79 initially increases almost linearly with water flux, although this drops off somewhat at higher fluxes. Expressing near-field releases as doses shows that, even for 2 orders of magnitude higher flux, the regulatory guideline would not be reached (Fig. 6.2).
Far-field
The key parameters for the Reference Case representation of far-field transport in water-conducting features with conservatively chosen geometrical characteristics are:

- Sorption distribution coefficients
- The path-length
- The water flow rate
- The extent of matrix diffusion
- The extent of dispersion during transport.

The sorption database is based predominantly on a literature review and is selected to represent the lower range of expected values. In view of the lack of site-specific measurements, however, calculations are also carried out with an even more conservative database. Although the conservative database results in higher dose maxima for some radionuclides, the total dose is still dominated by Cs-135, which changes little for this variant due to the relatively low retardation in the geosphere of this nuclide.
The representation of sorption by a simple distribution coefficient (Kd) is known to be an oversimplification of the real system. An improved representation of sorption involves use of non-linear isotherms, which represent the concentration-dependence of partitioning between aqueous and solid phases. Although insufficient data are available to define isotherms for most elements, Cs is a notable exception which has been very extensively studied. Representation of Cs sorption by a Freundlich isotherm delays breakthrough and slightly decreases the maximum release rate for the conservative representation of water-conducting feature geometry, but the consequences for resultant predicted doses are not significant.

The assumed flow path length through the LPD in the Reference Case is 200 m. This is based on a minimum separation of an emplacement tunnel from a major water-conducting fault or the HPD, which will be 100 m, but also accounting for flow path tortuosity. To evaluate the sensitivity of calculated releases to this parameter, calculations were repeated for a flow path length of 100 m (as a minimum value) but the calculated dose profile shows little sensitivity to this parameter although the contributions from individual nuclides change somewhat.

To evaluate sensitivity to groundwater flow rates, calculations were repeated for flow rates one and two orders of magnitude higher than the Reference Case value. As noted above, increasing the water flux also increases the releases from the near-field and this was taken into account in these calculations. Increased groundwater flow decreases the effectiveness of both the geosphere and (to a lesser extent) the near-field so that this parameter considerably influences resultant doses - decreasing breakthrough times and increasing dose maxima for many radionuclides. For the highest flow rates, contributions to total dose from Tc-99 and the \( ^{4N+2} \) actinide chain become increasingly significant (Fig. 6.2), although total doses still lie below the regulatory guideline.

The consequences of reducing the effectiveness of matrix diffusion by either decreasing the assumed diffusivity or the depth of accessible matrix and of reduced dispersion during transport have also been assessed and shown to have insignificant effects on total predicted doses, although releases may occur at earlier times and contributions from radionuclides other than Cs-135 may increase somewhat.

### Biosphere

Parameter variations in the biosphere analysis were predominantly aimed at examining model sensitivity to factors such as the extent of nuclide sorption on soil, the irrigation regime specified and the erosion rate. In no case did these variations increase total dose by as much as an order of magnitude.

The Reference Case assumes that the repository is located in siting Area West. However, some calculations explicitly focused on siting Area East have also been carried out. The main difference between the two areas is the expected groundwater flow rate through the repository - which is significantly higher in Area East. There are also differences in the sorption of some elements (notably Tc and U - resulting from differences in groundwater chemistry) and in the geography of the discharge zone.
(which could be a small side valley of the Rhine). Although doses are still well below regulatory guidelines, the maximum calculated releases (Fig. 6.3) are more than an order of magnitude higher than for the Reference Case (Fig. 6.1) and the duration of higher releases is much longer (due principally to the increased significance of Tc-99 and the "4N+2" actinide chain).

6.3.2 Alternative model assumptions

The alternative model assumptions considered within the Reference Scenario are all related to far-field transport. These include:

- Alternative representations of water-conducting features
- Assuming matrix diffusion in both altered and unaltered wall rock
- Including colloid-facilitated nuclide transport
- Groundwater flow variation in different water-conducting features
- Additional nuclide retention in major water-conducting faults.

![Graph](image_url)

Fig. 6.3: Time development of the annual individual doses for a repository located in Area East
Three distinct types of water-conducting features have been identified in the crystalline basement; these can be represented by a range of extreme geometric simplifications which also take into account whether matrix diffusion is limited to altered wall rock or not. The Reference Case was selected as the variant which conservatively minimises retardation (cataclastic zones or jointed zones, widely spaced channels and only limited matrix diffusion).

The representation of the geometry of the water-conducting features in the far-field transport model can have a dramatic effect on the calculated efficiency of the geosphere barrier. Assuming closely-spaced, narrow channels in such cataclastic zones or jointed zones would result in sufficiently high retardation that effectively no releases would occur within a million years (Fig. 6.4).

The assumption that matrix diffusion extends further into the wall rock increases the efficiency of the geosphere barrier further.

The microporous structure of highly compacted bentonite ensures that it acts as an efficient colloid filter and hence radionuclides are released from the near-field in true solution only. Even though natural colloid concentrations are measured to be very low (e.g. colloids may be released from the outer bentonite surface), colloid-facilitated radionuclide transport through the geosphere cannot be precluded. Conservatively assuming a high colloid concentration and that these colloids do not interact with the surrounding rock (either due to sorption on rock surfaces or diffusion into matrix porosity), the effects of such colloids on nuclide transport were assessed for a range of representations of water-conducting feature geometries. The results of these calculations show that, for cases where the geosphere barrier is very effective, colloid-facilitated transport may decrease this effectiveness significantly, although releases are still reduced significantly during transport through the geosphere. For the representation of the water-conducting feature chosen in the Reference Case, where the effect of the geological barrier is already rather limited, the decrease in performance due to colloid transport is much less significant.

The Reference Case assumes that all radionuclide transport from the repository occurs in features which are effectively identical in terms of geometry and flow rate. In reality, flow will vary between different water-conducting features depending on their transmissivities and porosities. The consequences of this have been assessed in a simple manner by distributing releases between features with the reference groundwater flow and values one and two orders of magnitude higher. This analysis clearly shows that performance can be completely dominated by a few flow paths with unfavourable properties in terms of flow rate. Although credit can certainly be taken for the performance of the geological barrier, analyses will probably need to involve reasonably conservative choice of parameters in order to be robust because of the great difficulty in excluding the presence of a few "fast" flow paths - even if their likelihood is very small.
Fig. 6.4: Time development of the annual individual doses for different representations of the geometry of water-conducting features. a) Reference Case: cataclastic zones or jointed zones with widely-spaced channels; b) Alternative Geometry: cataclastic zones or jointed zones with closely-spaced channels
The far-field transport calculations presented above have focused entirely on flow through the LPD host rock but, in reality, further transport through hundreds of metres of either major water-conducting faults or HPD basement will occur before release into overlying aquifers. The effect of additional retardation during transport through such rocks has been evaluated but is seen to be negligible relative to the barrier roles of the near-field and the LPD.

6.4 Alternative scenarios

The discussion of alternative scenarios within the formal scenario development procedure is generally limited to demonstration of their very low probability; demonstration that their consequences are covered by the parameter/model assumption variations described above; or that they contribute to safety (reserve FEPs), and so can be conservatively neglected.

Four types of alternative scenarios have, however, been analysed separately:

- A deep groundwater well
- Scenarios which bypass or reduce efficiency of the geosphere
- Altered climate biosphere scenarios
- The Robust Scenario.

Within the first category of scenarios, calculations have been carried out for the case of extraction of deep groundwater for use as drinking-water. In this case, the extent of dilution is decreased by comparison with the Reference Case, but this is partially compensated by the absence of accumulation in biosphere compartments, with the net result that the time and magnitude of the maximum calculated dose is very little changed.

Failure of shaft and tunnel seals can decrease considerably the efficiency of the geosphere. Higher water fluxes also perturb the near-field, but its efficiency is still high. Furthermore, even when the LPD geosphere is bypassed, transport along tunnel/shafts gives significant retardation. The result is that releases are still well below regulatory guidelines.

Based on historical and geological records, climatic fluctuations occur on a timescale of centuries to millennia, with the most dramatic cycling between major glacial and inter-glacial periods occurring on timescales of $10^4$ to $10^5$ a. It is, of course, still an open question if anthropogenic effects could alter the course or timescale of such cycles. Nevertheless, even though it is impossible to predict how climate will evolve over the next $10^6$ a, reasonable assumptions about future climatic extremes can be made in order to determine how sensitive calculated doses are to the model biosphere. For such altered climates, human behaviour patterns are assumed based on those found in such climatic zones at the present time (e.g. in a periglacial climate, present-day subsistence agriculture is taken to be impossible and reindeer farming as currently practised in Northern Scandinavia is considered a more useful model).
Arid and humid scenarios were calculated assuming, simplistically, that they persist over the entire period modelled. The form of the calculated dose profiles is roughly the same as the Reference Case, with values about an order of magnitude higher in the arid case and a factor of about 2 lower for the humid case. These differences can be attributed to changed water use, with increased irrigation of land under drier conditions maximising the consequences of release, while absence of artificial irrigation and increased fluxes of water reduce doses when the climate is wetter.

A cold (tundra) climate is characterised by permafrost which effectively isolates the surface environment from deeper aquifers. Dose results predominantly from the dust-lichen-reindeer\(^1\) pathway. Calculations indicate that resultant doses are orders of magnitude lower for this climate than for any of the alternatives.

Glaciation and the gradual processes of geomorphological change will alter the geography of the groundwater discharge zone over the next \(10^6\) a. In particular, the Rhine gravels, into which discharge would be expected under current conditions, are likely to go through future phases of erosion and re-deposition. Complete removal of these gravels would result in the Rhine flowing directly on the exposed crystalline basement and doses have been calculated for this scenario. As an extreme variant, doses were also calculated for releases directly into a deep soil with no underlying aquifer - although it is not expected that such a situation would arise. The former scenario leads to much lower doses due to higher dilution in the river water than would occur if releases were directly to the deep soil. The latter scenario leads to doses about an order of magnitude higher than in the Reference Case, due to decreased dilution.

In no case do these scenario variants approach the regulatory limits. These scenarios tend to maximise differences as alternative biosphere representations are generally assumed to persist over the entire period modelled whereas, in reality, continuous variation in human behaviour, climate and geomorphology will tend to smooth out extremes. In particular, doses will be negligible over the glacial and periglacial periods expected to prevail over most of the next million years.

The concept of robustness and the requirements for a Robust Scenario were previously presented in section 5.2. Taking into account the sensitivity of the predicted performance to parameter and conceptual model uncertainties presented above, the Robust Scenario is defined thus:

- The engineered barriers perform at their minimum design level.
- The geosphere does not provide any retardation of released radionuclides but does limit flow through the repository area.
- The Reference Case biosphere is assumed.

\(^{1}\) In this environment, the main route for radionuclide transfer from soil to man involves dust trapped by lichen which are then eaten by reindeer, themselves a source of meat and milk for the local populace.
This reflects reasonable confidence in the performance of the near-field whilst, due to uncertainties in water-conducting feature geometry and flow rate distribution and the possible role of irreversible uptake on colloids, the geological barrier is relied on only to protect the engineered barriers and limit total water flux through the near-field. As previously noted, the biosphere does not have a specific barrier role and is simply a standardised representation used to allow releases to be expressed as doses.

Even with this definition, the choice of a representation of the minimum design level performance of the engineered barriers is somewhat subjective. The Robust Scenario is thus analysed by three near-field calculations representing different interpretations of this minimum performance:

a) The near-field parameter set is chosen on the basis that these parameter values are all moderately conservative and conservatism of the overall model is ensured due to "reserve" FEPs which are excluded from this analysis.

b) The parameter set as above, with the additional conservatism of assuming a zero concentration outer boundary condition for the calculation of transport through the bentonite, allowing for uncertainty in groundwater fluxes through the repository and the characteristics of the excavation disturbed zone surrounding the emplacement tunnels.

c) A highly conservative parameter set with increased glass corrosion rate, elemental solubilities and reduced sorption on bentonite, allowing for residual uncertainties of these parameters.

The results for the last of these options are shown in Fig. 6.5. Cs-135 is an important contributor to total dose in all cases but, especially for the options b) and c) above, Tc-99, Sn-126 and the actinide chains are also very important. Nevertheless, even for these very pessimistic calculations, doses would lie below the regulatory guideline, indicating that a robust demonstration of safety has been achieved.

6.5 Performance assessment results in perspective

PG'85 was a first-generation assessment which was carried out on a legislatively imposed timescale and at a time when such integrated assessments were novel (being preceded only by the Swedish KBS-1,-2-3 series). Kristallin-I builds on the PG'85 framework but can also be seen in the context of the large number of assessments carried out in the intervening 8 years. In the latter regard, it should be noted that very similar disposal concepts (vitrified HLW in a steel canister horizontally emplaced in clay-backfilled tunnels) have been studied in several countries (Belgium, Spain, Japan) and their assessments indicate good performance of the near-field similar to that noted in Kristallin-I. Similarly, several countries considering crystalline basement as a disposal option (e.g. Sweden, Finland, Canada, Spain) have evolved similar layout schemes (in panels between major fault zones) and have shown that the geological barrier can protect the near-field and can provide very significant retardation of transport and consequent decay of key radionuclides.
In a focused review (NEALL 1994), Kristallin-I models, databases and results have been compared in detail to those from recent performance assessments and, additionally, predicted doses and risks compared to those from natural sources. The latter comparison is particularly instructive (Fig. 6.6) as it clearly indicates that predicted doses are generally at a level comparable to those derived from common practices which are not normally considered to be radiologically hazardous - e.g. drinking mineral water. This analogy is rather apt, as it is to be expected that water flowing through a repository will not accumulate significantly more radioactivity than that derived naturally from the rock.

Fig. 6.5: Time development of the annual individual doses in calculations modelling the Robust Scenario, with highly conservative values for glass corrosion rate, sorption constants in the bentonite and solubility limits, and release from the near-field passing directly into the biosphere.
Natural radiation exposures in Switzerland

Regulatory Guideline: 0.1 mSv a\(^{-1}\)

- 0.05 mSv a\(^{-1}\): Intercontinental flight per year
- 2.8 x 10\(^{-3}\) mSv a\(^{-1}\): 0.2 litre mineral water per day
- 1.9 x 10\(^{-3}\) mSv a\(^{-1}\): watching TV one hour per day

7.7 x 10\(^{-4}\) mSv a\(^{-1}\): 0.2 litre of average Swiss mineral water per year (small glass)

Fig. 6.6: Reference Case predicted doses in the Kristallin-I analysis compared to natural sources of radiation exposure (taken from NEALL 1994)
7 EVALUATION OF THE CRYSTALLINE BASEMENT AS A POTENTIAL HOST ROCK

7.1 Requirements for an acceptable HLW repository host rock

The performance assessment summarised in the previous Chapters clearly demonstrates that acceptable safety (releases well below the regulatory guideline) can be reasonably assured for the Nagra HLW disposal concept based only on the expected performance of the engineered barriers and dilution during the transport of near-field leachate to the accessible environment. In order for the near-field to perform as expected, the host rock around the engineered barriers plays a critical role in ensuring that they are physically protected from disturbance (due to either natural or anthropogenic events or processes) and that the low water flux and hydrogeochemical environment is conducive to their longevity. It must be possible to extrapolate the key characteristics of the host rock for a time period of the order of a million years, and to demonstrate that they are applicable to a specific site.

The analysis also shows that the host rock can function as a very effective additional barrier - reducing the low release rates of radionuclides from the near-field yet further. Such a barrier role for the host rock is not critical to the safety case, but is desirable given the principles of the multibarrier concept adopted.

In addition, from a practical point of view, it must be demonstrated that the repository can be constructed at acceptable cost and operated safely. It is also advantageous that the host rock considered is similar to that investigated in other national programmes in order to benefit from the pooling of expertise and collaboration in generic research.

In the following section, experience gained since PG’85 is summarised in order to allow an evaluation of the crystalline basement of Northern Switzerland as a potential host rock given the requirements noted above. This is followed by an overview of the further site characterisation and research studies which can help to provide a demonstration of siting feasibility and later to support eventual application for a construction and operation licence for a repository.

7.2 Suitability of the crystalline basement of Northern Switzerland

The host rock requirements noted in the previous section are summarised in Table 7.1 and are now discussed in turn for the specific case of the low-permeability domain of the crystalline basement in Area West.
Table 7.1: Requirements for a HLW repository host rock

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Crystalline basement / Area West</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Essential for the demonstration of long-term safety</strong></td>
<td></td>
</tr>
<tr>
<td>. Physical isolation of the engineered barriers</td>
<td>. Good mechanical stability of deep crystalline blocks</td>
</tr>
<tr>
<td>. Low water fluxes through repository</td>
<td>. Ensured by low permeability of the host rock and low hydraulic gradients at repository depth</td>
</tr>
<tr>
<td>. Favourable hydrochemistry</td>
<td>. Reducing conditions certain</td>
</tr>
<tr>
<td>. Adequate water fluxes in overlying formations (=&gt; dilution)</td>
<td>. pH neutral - alkaline, low to medium salinity</td>
</tr>
<tr>
<td>. Long-term stability</td>
<td>. Ensured by geographical situation and hydrogeological properties of MWCFs, HPD, overlying sediments and gravels in the discharge area</td>
</tr>
<tr>
<td>- Tectonic</td>
<td>. Block of LPD between major faults favourable</td>
</tr>
<tr>
<td>- Hydrogeological</td>
<td>. Block of LPD below sediments and between MWCFs favourable</td>
</tr>
<tr>
<td>- Chemical</td>
<td>. Buffered by rock/water interaction</td>
</tr>
<tr>
<td>. Adequate sealing of tunnels/shafts possible</td>
<td>. Excavation disturbed zone (EDZ) likely to be small</td>
</tr>
<tr>
<td>. Low risk of accidental intrusion</td>
<td>. Sealing has been demonstrated in hard rocks</td>
</tr>
<tr>
<td><strong>Desirable for the demonstration of long-term safety</strong></td>
<td></td>
</tr>
<tr>
<td>. Radionuclide retardation (and decay) in the geosphere</td>
<td>. Delayed release of key nuclides ensured by sorption along flow paths</td>
</tr>
<tr>
<td>. Low risk of accidental intrusion</td>
<td>. Extensive retardation (decay) possible for favourable geometry of flow rate in water-conducting features</td>
</tr>
<tr>
<td><strong>Essential for the demonstration of siting feasibility</strong></td>
<td></td>
</tr>
<tr>
<td>. Site exploration strategy to</td>
<td>. Practicality demonstrated in Phase I</td>
</tr>
<tr>
<td>- Confirm geo-database</td>
<td>. Achievable with inclined boreholes/seismic/tomography/crosshole hydro tests</td>
</tr>
<tr>
<td>- Identify MWCFs</td>
<td>. Construction costs can be reasonably well specified</td>
</tr>
<tr>
<td>. Economic feasibility</td>
<td>. Exploration costs roughly estimated</td>
</tr>
<tr>
<td>. Evaluation of SF / TRU</td>
<td>. Work in progress</td>
</tr>
<tr>
<td>. Clarification of land use constraints</td>
<td>. Range of options throughout Area West</td>
</tr>
<tr>
<td><strong>Desirable for the demonstration of siting feasibility</strong></td>
<td></td>
</tr>
<tr>
<td>. Safety during construction / operation</td>
<td>. Deep excavation in crystalline rocks well established</td>
</tr>
<tr>
<td>. International consensus</td>
<td>. Crystalline basement selected in Sweden, Finland and Canada</td>
</tr>
<tr>
<td></td>
<td>. Options in France, Japan, Spain, etc.</td>
</tr>
</tbody>
</table>
7.2.1 **Suitability with respect to demonstration of long-term safety**

In order to make a convincing safety case based on the performance of a robust near-field, it must be possible to demonstrate that the engineered barriers will evolve as expected. A major justification for deep geological disposal is the physical isolation of the repository from violent surface processes and events which could perturb these barriers (e.g. hurricanes, floods, acts of war). The deep crystalline basement in Area West can be regarded as particularly favourable from this point of view as no probable natural process has been postulated which could cause significant physical disturbance of the proposed repository on a $10^6$ a timescale. Highly improbable events which could have an effect (e.g. meteorite impact) would be so catastrophic that the consequences of perturbation of the repository would be negligible in comparison.

One process which could, over an extended time, disrupt the engineered barriers would be erosion of the bentonite by flowing groundwater. Rather large groundwater flows would, however, be needed to have a significant effect. Water flow in the low-permeability domain of the crystalline basement will be low and generally localised in discrete water-conducting features. It is foreseen that any such features which carry particularly high water fluxes will be identified during site characterisation and avoided when emplacing waste. It may also be noted that both the low average water flux in the low-permeability domain and its localisation in specific zones contribute to increase the efficiency of the bentonite as a transport barrier for radionuclides by increasing radionuclide diffusion times from the waste form to the host rock (lower concentration gradients, longer pathways). This increased efficiency is, however, not absolutely essential to the safety case.

The performance of the various engineered barriers depends, to some extent, on the groundwater chemical composition. In this regard, a key factor is that the water should be chemically reducing (giving low canister corrosion rates and generally low radionuclide solubilities) - which can be assured for the crystalline basement on the basis of the regional hydrochemical studies carried out. Groundwaters in the crystalline basement also have favourable pH values (in the neutral to alkaline region) and tend to have low to medium salinity, which is not essential to ensure near-field performance but simplifies the analyses needed to demonstrate such performance. The bentonite backfill plays a very important role in the engineered barrier system and confidence of its longevity is enhanced for the crystalline host rock by the identification of similar smectite clays as products of recent rock/water interaction in water-conducting features and analogue studies indicating long persistence of bentonites in similar geochemical environments.

Although it is not normally regarded as a safety barrier, the importance of the contrast between the low water flux through the low-permeability basement and the much higher fluxes in major water-conducting faults, higher-permeability crystalline basement, overlying sediments, gravel aquifers and surface waters should be emphasised. Dilution along the flow path considerably decreases the concentration of any released radionuclides and hence also their potential hazard. The geography of Northern
Switzerland ensures that, in the discharge zone of groundwaters passing through the repository area, large surface and near-surface water fluxes from catchments in the Alps and Black Forest can be relied upon (in contrast, for example, to disposal concepts in arid environments).

The features noted above allow appraisal of the repository performance under present conditions but, as quantitative analysis extends for periods in the order of a million years, the extent to which changes may occur over long periods must be considered. With regard to physical protection, disposal in a block of basement surrounded by major faults is particularly favourable. Over the next million years tectonic activity will occur, but it can be assumed that the rock movements will be focused on existing major fault zones - as it has been in the past. Within the LPD, movements will be very limited and, again, focused on existing smaller faults - which would generally be avoided during waste emplacement. Formation of new faults is considered to be very unlikely in this environment.

Stability of the deep hydrogeological regime in the basement in Northern Switzerland is assured by its structural stability and the presence of aquifers and aquitards in the overlying sediments which effectively decouple it from possible perturbations of near-surface hydrology. Further decoupling may occur if the faults which determine repository layout have higher permeabilities (hydraulic cage effect).

Regional hydrochemical and isotopic studies present a consistent picture of the evolution of the groundwaters in the crystalline basement in Area West by slow rock / water interaction over tens of thousands of years. The expected stability of the deep groundwater flow system and the vast quantities of rock available in relation to the low water flux argue for very stable hydrochemistry in this region.

Surface hydrology is influenced by climate and landform evolution (uplift, erosion, deposition, etc.) and thus can be expected to vary considerably over the next million years. Nevertheless, the region can be expected to remain dominated by a major river valley and hence there will be significant dilution potential for any releases from the basement to the surface. The only identified exception to this generalisation would be during periods of extensive glaciation. In this environment, exfiltration is expected to be negligible due to the presence of permafrost but, in any case, such a continental ice-sheet would be expected to be totally depopulated.

It is necessary to demonstrate that all openings (shafts, tunnels, boreholes, etc.) can be adequately sealed. Sealing technology is currently under development but has, to some extent, been demonstrated for crystalline rocks (e.g. at Stripa). Long-term performance of seals may be helped by the limited extent of the expected excavation disturbed zone (EDZ) around openings in the crystalline basement. Performance assessment has also shown that the geosphere will delay the releases of key radionuclides and could, potentially, act as an extremely efficient additional barrier, such that releases are practically zero for the period over which quantitative analysis is reasonable. Conclusive demonstration of such a powerful barrier role is not possible at present but may be achievable given more site characterisation data, especially for the rock.
immediately surrounding the emplacement tunnels. Such a demonstration is not, however, essential to the safety case as shown by the Robust Scenario calculations.

It is impossible to preclude anthropogenic perturbations, but the absence of any obviously exploitable natural resources in the basement which would justify exploitation minimises the risk of inadvertent human intrusion. Deliberate intrusion cannot be prevented but, for this deep disposal concept, would involve considerable effort and would not be lightly undertaken. Retrievability of the waste is not a design criterion but, if this were ever desired by future generations, it would be aided by the mechanical stability of this host rock.

In conclusion, the low-permeability domain of the crystalline basement of Northern Switzerland in siting Area West is confirmed as providing the essential requirements of a host rock for a HLW repository.

7.2.2 Suitability with respect to demonstration of siting feasibility

Despite the very clear safety features of a crystalline host rock with overlying sediments, from a practical point of view, a major disadvantage is the difficulty of characterising this rock due to the lack of surface exposure of the basement in the area of interest. As a result, this first phase of exploration must be based on interpretation of data from surface geophysics complemented by analyses of a limited number of boreholes. Nevertheless, experience gained in the regional investigation programme allows confidence in the practicality of confirming if the essential requirements in terms of geological conditions are met at a particular site. As discussed further in the following section, an exploration strategy has been devised for the crystalline basement which progresses sequentially from site characterisation from the surface to underground site confirmation.

The main uncertainty identified in the regional studies was in the distribution of major water-conducting faults which would influence repository siting. Statistical analysis of the expected distribution of such faults (Fig. 7.1) indicates that the probability of finding one or more blocks of sufficient size at any given location is high. Site-specific studies would allow this model to be supported by local data and might even directly identify likely emplacement blocks. It should be emphasised, however, that exploration from the surface cannot be expected to provide sufficient data for an application for a repository construction permit, but it would allow the costs of underground site confirmation to be assessed in the light of the remnant risk that the specific site investigated would prove unsuitable. A multi-level repository (Fig. 7.2) could be located in a single block of LPD crystalline rock with an area of ~0.3 km$^2$ and a usable thickness of ~200 m. Reducing the respect distance from major water-conducting faults would allow even smaller LPD blocks to be used (down to ~0.1 km$^2$). It appears probable that such blocks could be found within a siting area (~3 x 3 km, say).
Fig. 7.1: Examples of representations of faults in the crystalline basement of Northern Switzerland. Shaded blocks indicate sites larger than 0.1 km² (light grey), 0.25 km² (medium grey), 0.50 km² (dark grey) and 1 km² (black). The concentric circles represent distances of 500, 1500 and 2500 m from a randomly selected point.
Fig. 7.2: Sketch showing option of multiple-level emplacement in small-size blocks; 3 layers in a block of $-0.3\,\text{km}^2$ needed for option with 20 m emplacement tunnel pitch which could be reduced further to $-0.1\,\text{km}^2$ if the respect distance from major water-conducting faults is reduced.
It is important to note that the siting Area West is rather small, relatively highly populated and contains extensive areas of environmentally protected land. As part of the siting feasibility demonstration, a preliminary study has shown that repository siting would not be unduly limited by land planning constraints. The relatively small surface facilities for repository construction and operation could be located at a number of sites throughout the area and provision of required road and rail links would not be especially problematic.

It should also be noted that the current waste management concept envisages co-disposal of spent fuel and long-lived intermediate-level waste with vitrified HLW. The long-term safety of these waste types must thus also be further assessed to determine if they place any additional constraints on the host rock or the specific site.

Although not essential for demonstration of siting feasibility, a number of further factors need to be assessed in the evaluation of the crystalline basement. While emphasis is correctly placed on the demonstration of long-term safety, the conventional (and radiological) risks associated with repository construction and operation must be considered. The crystalline basement is certainly an attractive option for such a deep repository in this regard because of the mechanical stability of the rock and the low risk of practical problems such as explosive gas ingress. Relatively high rock temperatures and potentially high radon releases will have to be taken into account, but should be readily handled by appropriate ventilation. Precautions would be taken to avoid high water inflow rates into workings - both to ease operational requirements and to minimise potential influences on mineral- or thermal-water wells.

Finally, the existence of extensive programmes investigating crystalline host rocks in other countries is a positive factor which should not be underestimated. Major HLW programmes have focused on crystalline host rocks in Sweden, Canada and Finland. Even though these cases all involve spent fuel disposal in crystalline shield environments, there is considerable common ground in characterisation techniques and site investigation methodology. Further established programmes in Japan, France and Spain consider crystalline basement as a host rock option. In these cases, the stratigraphic and tectonic setting may be more analogous to that in Switzerland and considerable opportunities exist for sharing of experience and collaborative research. This is particularly true for Japan, where effort focuses on disposal of vitrified HLW and a disposal concept has been developed which is very similar to the Kristallin-I case.
7.3 Future studies of the crystalline host rock option

As noted above, work to date has confirmed the arguments which led to the selection of the crystalline basement as a potential host rock for a HLW repository. There are, however, still some open questions which need to be resolved for the demonstration of siting feasibility and for subsequent application for repository construction and operation licences. The proposed future programmes of field work and associated research and development are outlined below, with specific discussion of the input of resultant data to the Entsorgungsnachweis project.

7.3.1 Site characterisation studies

This section reviews the strategy devised to characterise further a crystalline site from the surface (Phase II) to the stage where the location of a shaft could be defined and exploration underground (Phase III) could be carried out in order to specify repository layout and form the basis of an application for a licence to construct and operate a repository at this site.

The main aim of Phase II is a demonstration (Entsorgungsnachweis) that the likelihood of suitable blocks of low-permeability crystalline basement existing at a specific site is high enough to satisfy regulatory requirements and to justify moving on to future subsurface characterisation in Phase III, assuming that a decision is made to build a HLW repository in Switzerland. The major technical output of Phase II is thus determination of the location of the LPD/HPD interface and mapping and characterisation of major water-conducting faults. Because of the overlying sediments which preclude direct observation of the crystalline basement, Phase II exploration is based on localised boreholes and geophysics (Fig. 7.3).

On the basis of experience gained during Phase I, it is clear that the applicability of surface geophysical techniques is limited and that no current non-invasive methodology allows unambiguous determination of structures within the crystalline basement. A localised 3D reflection seismic survey should, however, be able to identify those major water-conducting faults which cause significant offsets (>~20 m) in seismic reflectors in the overlying Mesozoic cover. Seismic tomography data may, additionally, allow the orientation of features identified during drilling to be established.

The main source of geological information will be gained from cored deep boreholes. As the major faults tend to be sub-vertical features, inclined boreholes are best suited to their localisation and characterisation. A concept has been developed in which a series ("star" array) of boreholes is drilled from a single location (Fig. 7.3). Confirmation of the presence of LPD crystalline basement at suitable depth is obtained by an initial vertical borehole (with associated fluid logging and hydrotests) and the characteristics of the LPD and any faults encountered can then be determined using
Fig. 7.3: Illustration of the proposed investigation concept for characterisation of the crystalline basement
core observation, geophysical logging, hydrochemistry etc. Inclined boreholes subsequently drilled from the same site are focused on identification of faults (core and fluid logging) and determination of their orientation and large-scale hydraulic properties via seismic tomography and crosshole hydrotecting, respectively.

Depending on the frequency and orientation of the faults identified, the presence of one or more LPD blocks of sufficient size to host all or part of a repository may be directly inferred. Even if this is not the case, the frequency and orientation of major water-conducting faults encountered allows the general conceptual model of their distribution in the investigation area to be tested and refined, and the probability of suitable blocks existing in the neighbourhood to be better assessed.

The full requirements for Phase II depend very much on initial findings - if the site selected for the initial boreholes is very favourable, it may be possible at that stage both to establish a potential repository layout and identify a potential location for an access shaft. In the case of less favourable results, or a desire to optimise repository layout (using blocks of LPD which are as large as possible, to minimise construction costs), further inclined boreholes or, indeed, another array in the vicinity may be desirable. Even in the case of identification of at least one suitable block of LPD, however, given the desire to locate the access shafts outside the emplacement panels, it may be necessary, at a later stage, to sink one or more further boreholes to confirm a potential shaft location outwith the area covered by the borehole array.

In the case of extremely unfavourable findings (for example if LPD is not encountered or fault size or frequency is much greater than expected), the decision would need to be taken if a further investigation could be carried out in the same siting region or if a different siting region should be examined. This decision would be based on a geological assessment of the probability of such poor conditions being either localised or general.

Assuming favourable results from Phase II, the first stage of Phase III would involve sinking a shaft to repository depth (probably preceded by a series of monitoring/confirmatory boreholes unless those drilled in Phase II are sufficient for this purpose). Investigations during shaft sinking and additional horizontal boreholes will provide input for designing an underground characterisation facility which would allow characterisation and long-term testing of the host rock. In parallel, pilot galleries will be constructed to confirm the geological model of the site and to establish the detailed layout of the repository. Only at the end of this stage of characterisation is it expected that the geological database will be sufficient to allow application for construction and operation licences, but the Phase II work must ensure that the risk of unfavourable surprises at this final stage is sufficiently small. The detailed investigation programme for this phase will depend not only on the findings from earlier investigations but also on developments in technology (as the work will not be carried out until sometime next century) and hence cannot be planned in detail at present.
7.3.2 Associated research and development

The safety analysis presented as part of the Kristallin-I project demonstrates the feasibility of safe HLW disposal on the basis of a robust near-field analysis. There are, nevertheless, some areas in which the supporting case could be further strengthened (e.g. better support for key databases such as radionuclide solubilities). Further research may allow the near-field model to be significantly improved by taking credit for "reserve FEPs" (cf. Chapter 5); this may allow even better performance to be demonstrated and thus reduce further the requirements on the host rock barrier function. In the long term, it is also intended to maintain a watching brief on developments in relevant technical disciplines which might allow improved performance to be demonstrated based either on new modelling techniques (e.g. mechanistic models of solute transport through compacted bentonite) or changed design (e.g. new canister materials such as strong ceramics). Given the long timescales before implementation of a HLW repository, significant developments in many technical fields are to be expected.

The relatively pessimistic analysis of far-field radionuclide transport might be greatly improved on the basis of detailed analysis of core material obtained during site characterisation - including studies of the structure of water-conducting features, the porosity of surrounding rock and radionuclide sorption on relevant minerals and rocks. More fundamental studies of solute transport in crystalline rock (as in the ongoing Nagra/PNC study at the Grimsel Test Site) will also contribute to supporting the case for an efficient far-field barrier.

Other geological questions (e.g. the extent of the EDZ, development of sealing technology) are addressed by studies carried out at the Grimsel Test Site and other test facilities abroad (e.g. URL in Canada, Äspö in Sweden).

In order to support the concept of co-disposal of spent fuel and TRU with HLW, work is underway to develop comprehensive near-field models for both these types of waste. For spent fuel, a general review will allow the requirements on the near-field barriers to be specified and hence a disposal concept to be defined. It is envisaged that most of the data needed for this analysis can be transferred over from the vitrified waste analysis or exchanged in collaborative agreements with other national programmes and thus an experimental programme to characterise spent fuel will not be required.

Detailed analysis of TRU will be based on data and models developed in the L/ILW programme, but further development of these will be needed. As there is currently considerable international interest in this topic and much of the work involved is fairly generic, it is planned that much of the development needed will also be carried out within international collaborative projects.
7.3.3 Outline of input to Project "Entsorgungsnachweis 2000"

With the aim of demonstrating siting feasibility by the year 2000, it is clearly advisable to make plans which take into account the potential time delays and uncertainties in output from field studies. At the strategic level, this is done by planning characterisation of the crystalline basement in parallel to equivalent work on an alternative sedimentary host rock (cf. Chapter 1). In terms of the crystalline host rock exploration programme, the risks of delays during licensing, operational problems during site work and surprises in the local geology are minimised by focusing work at an existing borehole site which has been seen to be potentially favourable (i.e. Leuggern or Böttstein). Indeed, it would even be possible to make a case for siting feasibility at one of these locations based on the present analysis of existing data and improved performance assessment, given that the requirements on the hydrogeological properties and size of the required emplacement block(s) are significantly reduced relative to PG’85. Drilling of one or more inclined boreholes at such a site, supported by seismic tomography, would certainly provide additional information on the probability of finding a suitable siting block. In addition, such work would be needed to better constrain the costs of site exploration. Costs are not a major issue when assessing siting feasibility but would certainly be needed to allow a comparison of the sedimentary and crystalline host rock options in preparation for potential realisation of a HLW repository in the future.

More comprehensive safety analysis of spent fuel and TRU disposal in the crystalline basement at the site studied will also be provided for Project Entsorgungsnachweis 2000, along with a site-specific update of the Kristallin-I analysis for vitrified HLW. It is currently envisaged that this will focus on post-closure performance assessment but the aspects of safety during construction and operation will also be addressed - although in a less detailed manner.
8 CONCLUSIONS

In the introductory Chapter, the aims of Kristallin-I were presented. These may be summarised as:

- Updating the analysis presented in PG'85 with improved models and databases.
- Acting as a milestone in the HLW programme by identifying a site for Phase II.
- Serving as input for programme planning and public information.

In the following sections, an overview of the main conclusions of Kristallin-I is presented, which is structured by consideration of the extent to which the aims of the project have been met.

8.1 Progress since PG'85

PG'85 was a landmark study which established the basic feasibility of constructing a safe repository for HLW in the crystalline basement of Northern Switzerland. However, it was carried out at a time when the geological investigations were still at an early stage - a complete dataset was available from only one of the seven deep boreholes (Böttstein) and regional integration of data was rather rudimentary. Progress since PG'85 is thus especially evident in the development of the geological understanding of the basement in the region of interest and the representation of this understanding in a geological database for performance assessment. In particular:

- A much improved tectonic model of the region has been developed which allows potential siting sub-regions (Areas West and East) to be delineated and the understanding of the distribution of major faults within these areas to be formalised in a statistical model.

- A new suite of hydrogeological models have been developed, which are based on a synthesis of more extensive hydrological measurements but also directly consider the fault model developed and the interpretation of regional geochemical and isotopic measurements.

- Great effort has gone into detailed characterisation of water-conducting features observed in the deep boreholes, which has been synthesised into model representations of three classes of such features. These descriptions are supported by new literature studies to define the important sorption and matrix diffusion properties of these flow paths.

- Hydrochemical and isotopic data have been synthesised on a regional basis to provide a fairly consistent picture of slow groundwater evolution due to rock/water interaction which not only shows general groundwater flow patterns in the basement but also forms the basis for the definition of reference waters for the two potential siting areas.
Analysis of potential long-term tectonic evolution scenarios has underpinned the two bounding scenarios presented in PG'85 - particularly with regard to the quantification of expected uplift, erosion and movement along various sizes of faults in the areas of interest.

In addition, the geosynthesis report provides an integration of all the key information produced to date which, taken as a whole, provides confidence in the concepts developed in the various sub-disciplines (structural geology, hydrogeology, geochemistry, etc.).

The other main component of Kristallin-I, the performance assessment, has also developed significantly in the decade since the PG’85 analysis. The major advances have been:

- Construction of a more rigorous scenario development and analysis methodology which documents system understanding in a more complete and traceable manner and allows the quantitative calculations carried out to be structured in a more logical manner.

- Improvement in conceptual model development to better represent the system studied - particularly for the structure of the water-conducting features in the host rock.

- Extension of the capabilities of the model chain used for calculations - in particular explicitly accounting for near-field radionuclide retardation in bentonite and allowing consideration of non-linear sorption and colloid transport in the far-field.

- Improved and/or better justified databases for radionuclide release and transfer calculations (e.g. solubilities, sorption coefficients, etc.).

- Rock mechanical and thermal calculations to support conceptual layout studies which show how relatively small blocks of low-permeability basement can be utilised.

- Implementation of procedures to provide improved quality assurance (e.g. traceable calculation output names, formalised peer review).

- Extensive effort on model verification and validation as part of international studies, using natural analogues and via specific experiments.

- Updated reviews to put performance assessment results in perspective by comparison with comparable repository analyses and the assessments of other potential environmental hazards.

These developments appear, within the remit of Kristallin-I, to cover most of the open questions identified in PG’85 and the various reviews of this project prepared by the authorities (HSK 1987; KSA 1986).
8.2 Kristallin-I as a milestone in the Swiss HLW programme

Kristallin-I serves as an important milestone in the Nagra HLW programme by completing documentation of the Phase I regional investigation programme and presenting a strategy for further site-specific phases of investigation and identifying locations at which such work could be carried out. The regional characterisation demonstrated clear constraints on siting - predominantly due to the presence of the Northern Swiss Permo-Carboniferous Trough - which allowed two smaller potential sitting areas to be defined. These areas are separately analysed in both the geological synthesis and the performance assessment, from which it can be concluded that, although both areas are potentially suitable, Area West is better characterised and may be preferable in terms of expected repository performance. Area West is thus recommended as first priority for further characterisation investigations. This area is known to contain two regional fault zones which divide it into three sub-areas; of these, the more easterly contains two boreholes which have shown evidence of the local presence of usable thicknesses of low-permeability basement at a reachable depth.

An exploration strategy has been designed for Phases II and III of site characterisation from the surface and underground, respectively. Given the objectives and timescales specified for the next major milestone in the HLW programme - Project Entsorgungsnachweis by the year 2000 - it is prudent to minimise the risks of delay or of unexpected geological complications by focusing Phase II on the location of an existing deep borehole which suggests favourable local conditions - i.e. Leuggern or Böttstein. In terms of general site suitability, there is no single compelling argument when setting priorities between these two locations but Leuggern is favoured by being further from potentially disturbed areas near the PCT and less likely to be influenced by the Vorwalt fault zone. Given the main aim of finding suitably large blocks of LPD, Leuggern has been set as first priority, but Böttstein is retained as a backup option. The arguments used to justify the selection of these sites for future site characterisation studies are summarised in Fig. 8.1.

In terms of long-term development of a national HLW strategy, the two key endpoints of the Kristallin-I synthesis are the confirmation that crystalline rock is sufficiently promising to justify local exploration, and the selection of the preferred sites for this exploration. It is important to note that the specific location chosen - even in the event that very positive results are achieved in the exploration - is unlikely to be the exact location of a deep repository. At a local scale, optimisation of shaft access etc. would certainly lead to new shaft areas; on a regional scale the long times available to potential implementation mean that comparison with alternative sites in crystalline host rock is not excluded; at a national scale; the option of disposal in clay is available; and at an international scale the attractiveness of joint projects is obvious. Although Kristallin-I and the following Project Entsorgungsnachweis 2000 will certainly not lead to immediate or even early implementation of a HLW repository, the
goal of providing to the Swiss public a convincing and complete demonstration that we can, if necessary, dispose of HLW within our own borders remains a key element in our long-term waste management strategy.
Selection Arguments

- crystalline basement at accessible depth
- relatively low seismic activity
- E and W boundaries set by areas of tectonic complexity in the basement

- reduced area of accessible basement due to presence of Permo-Carboniferous Trough (PCT)

- no low-permeability domain (LPD) identified in Siblingen
- evidence of LPD from Boettstein and Leuggern boreholes
- Sub-regions defined by regional fault zones

- extensive LPD basement at Leuggern and Boettstein
- exploration concept based on several inclined boreholes from a single site
- risks of delays / surprises less if exploration from existing site
- Leuggern further from PCT / regional fault zone

Fig. 8.1: An overview of the arguments leading to selection of areas for further studies leading to siting demonstration
8.3 Kristallin-I as input to technical programme planning and public information

The methodology and databases developed within Kristallin-I form an infrastructure for analysis of other types of waste which would be included in a deep HLW repository (spent fuel and various types of long-lived, intermediate-level waste) and, indeed, for assessment of the potential of the Opalinus Clay as an alternative host rock. The Kristallin-I Reference Case forms a benchmark for comparison of the expected performance of different waste type/host rock combinations. The procedures established for development of robust scenarios allow minimum required performance of such systems to be evaluated.

An outline of plans for field studies and associated research and development work up to the end of the century was presented in the previous Chapter. The documentation of system understanding within the scenario development procedure allows potentially important areas of uncertainty to be identified, which serves as a basis for deriving a more detailed list of research objectives. The sensitivity analysis within the Kristallin-I performance assessment allows the relative importance of individual parameters to be evaluated, which forms a basis for assigning research priorities. In some cases, the range in which the value of a parameter is sensitive can also be defined, which then means that it is necessary only to establish that it is larger or smaller than a particular value rather than determining it exactly. The Kristallin-I Robust Scenario analysis indicates that there are relatively few critical parameter values which determine whether regulatory guidelines are met (e.g. elemental solubility limits).

Carrying out such robust scenario analysis for other waste type/host rock combinations as considered above would allow requirements and priorities for a comprehensive research programme to be established.

Finally, it should be noted that the Kristallin-I technical documentation forms the basis for deriving information packages for the general public. Indeed, this project summary report is structured to provide a less technical overview of the more comprehensive geological synthesis and performance assessment documents. In turn, the content of this report will be further condensed, at a still more general level, in the form of articles and brochures. As the HLW programme moves into a site characterisation phase for both crystalline basement and Opalinus Clay options, informing the population in the investigation areas becomes increasingly important. To improve public acceptance, the general procedures used should be as transparent as possible. Even if the details of the safety case are complex, the aim of robustness, the processes of quality assurance, peer review, verification and validation, the degree of international consensus and the requirements for future work should be made clear. The Kristallin-I project was planned with such output in mind and it is intended that it will provide a template for future studies of this type.
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