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結晶質岩における坑道閉鎖時の地質環境モニタリング技術に関わる情報収集

Information Collection Regarding Geoscientific Monitoring Techniques during Closure of Underground Facility in Crystalline Rock

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国立研究開発法人日本原子力研究開発機構（原子力機構）では、高レベル放射性廃棄物の地層処分技術に関する研究開発のうち深地層の科学的研究（地層科学研究）の一環として、結晶質岩（花崗岩）を対象とした超深地層研究所計画を進めている。この計画においては、原子力機構改革を契機に抽出された三つの必須の課題（「物質移動モデル化技術の開発」、「坑道埋め戻し技術の開発」、「地下坑道における工学的対策技術の開発」）の研究開発を進めている。このうち、坑道埋め戻し技術の開発においては、地下施設閉鎖時・後の地質環境の回復能力等を評価するとともに、地質環境条件に応じた埋め戻し技術の構築を目指す。また、長期の観測に必要なモニタリング技術の開発も実施することとしている。

以上を踏まえ、坑道埋め戻し技術の研究開発に資するため、先行して坑道の埋め戻しや、それに関わるモニタリングを実施している諸外国の結晶質岩中に建設された地下施設（研究施設や放射性廃棄物処分場）を対象として、坑道閉鎖に関わる制約条件、坑道周辺の地質環境条件、坑道閉鎖の方法・材料・工程、モニタリング方法の情報を収集・整理した。また、ヨーロッパ諸国で行われている坑道閉鎖試験やモニタリングに関わる国際プロジェクトについても情報収集・整理を行った。加えて、主にフィンランド、スウェーデンにおいて地下施設閉鎖に関わる計画立案、施工管理、モニタリング、安全評価に携わった実務経験を有する専門家にインタビューを行った。これらの情報収集・整理結果に基づき、瑞浪超深地層研究所における坑道全体を閉鎖する際の計画立案や施工管理、モニタリングに関わる考え方や留意事項、さらには坑道埋め戻し技術の開発に関わる試験研究に関わる留意事項を整理した。

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The Mizunami Underground Research Laboratory (MIU) project is being pursued by the Japan Atomic Energy Agency (JAEA) to enhance the reliability of geological disposal technologies through investigations of the deep geological environment in the crystalline host rock (granite) at Mizunami City in Gifu Prefecture, central Japan.

On the occasion of the reform of the entire JAEA organization in 2014, JAEA identified the critical issues on the geoscientific research program: “Development of modelling technologies for mass transport”, “Development of drift backfilling technologies” and “Development of technologies for reducing groundwater inflow”, based on the latest results of the synthesizing R&D. The purposes of the “Development of drift backfilling technologies” are to develop closure methodology and technology, and long-term monitoring technology, and to evaluate resilience of geological environment.

In order to achieve the purposes, previous information from the case example of underground facility constructed in crystalline rock in Europe has been collected in this study. In particular, the boundary conditions for the closure, geological characteristics, technical specifications, and method of monitoring have been focused. The information on the international project regarding drift closure test and development of monitoring technologies has also been collected. In addition, interviews were conducted to Finnish and Swedish specialists who have experiences involving planning, construction management, monitoring, and safety assessment for the closure to obtain the technical knowledge.

Based on the collected information, concept and point of attention, which are regarding drift closure testing, and planning, execution management and monitoring on the closure of MIU, have been specified.

Keywords: Mizunami Underground Research Laboratory (MIU) Project, Crystalline Rock, Monitoring, Closure

*Dia Consultants Co. Ltd.

目次

1. はじめに..1
2. 既存情報の収集・整理..2
2.1 坑道閉鎖に関わる要求事項..2
2.2 坑道閉鎖方法（材料，工程）..3
2.3 坑道閉鎖に関わるモニタリング..6
3. 専門家，実務者へのインタビュー..9
4. 瑞浪超深地層研究所の坑道閉鎖，モニタリングに関わる検討事項の整理..................11
4.1 坑道閉鎖時に満たすべき条件..11
4.2 坑道閉鎖にあたって考慮すべき地質・水理的特徴..12
4.3 坑道閉鎖方法..13
4.4 坑道閉鎖に関するモニタリングとモデリング..20
4.5 坑道閉鎖前または閉鎖時に実施すべき研究課題..20
4.6 スケジュールに関する制約条件..21
5. まとめ..24

参考文献..28

付録..29

Contents

1. Introduction 1
2. Review of existing information...2
2.1 Requirements for the closure 2
2.2 The closure concept 3
2.3 Monitoring of the closure...6
3. Information-gathering from experts 9
4. Strategy and plans for closing the MIU 11
4.1 Performance requirements of the closure...11
4.2 Boundary conditions for the closure design 12
4.3 Closure concept development 13
4.4 Monitoring and modeling of the closure 20
4.5 Technical challenges before the closure and during the closure process 20
4.6 Schedule constraints 21
5. Conclusion...24

References...28

Appendix..29

1. はじめに

国立研究開発法人日本原子力研究開発機構（以下、原子力機構）では、地層処分研究開発の基盤となる深地層の科学的研究の一環として、岐阜県瑞浪市において結晶質岩を対象とした超深地層研究所計画（日本原子力研究開発機構，2010）[1)]を進めている。この計画では、深部地質環境の調査・解析・評価技術の基盤を整備することを主たる研究目標としており、地表からの調査予測研究段階（以下，第 1 段階）、研究坑道の掘削を伴う研究段階（以下，第 2 段階）、研究坑道を利用した研究段階（以下，第 3 段階）の 3 つの段階に区分し研究を進め、調査の進展に伴う情報量の増加に応じた地質環境特性に関わる理解度や調査の達成度を順次評価している。

原子力機構の第 3 期中期計画期間（2015～2019 年度）においては、原子力機構改革を契機に抽出された三つの必須の課題（「物質移動モデル化技術の開発」、「坑道埋め戻し技術の開発」、「地下坑道における工学的対策技術の開発」）の研究開発を進めることとしている。このうち、坑道埋め戻し技術の開発においては、深度 500m の研究坑道において、坑道の一部を閉鎖し、地下水で冠水させることによって、地下水の水圧・水質および坑道周辺岩盤の化学的・力学的変化を観察し、地質環境の回復能力等を評価するとともに、地質環境条件に応じた埋め戻し技術の構築を目指すこととしている。あわせて、長期の観測に必要なモニタリング技術の開発も実施する。さらに、第 3 期中期計画期間末までに、研究の進捗状況などを確認し、跡利用検討委員会での議論も踏まえ、坑道埋め戻し等のその後の進め方について決定することとしている。

以上を踏まえ、「坑道埋め戻し技術の開発」の研究開発計画を具体化することを目的として、先行して坑道の部分的な埋め戻しやモニタリングを実施している諸外国の結晶質岩中に建設された地下施設（研究施設や放射性廃棄物処分場）を対象とした情報の収集・整理を行った。具体的には、坑道閉鎖に関わる制約条件、坑道周辺の地質環境条件、坑道閉鎖の方法・材料・工程、モニタリング方法に関わる情報を収集・整理した。また、ヨーロッパ諸国で行われている坑道閉鎖試験やモニタリングに関わる国際プロジェクトについても情報収集・整理を行った。加えて、主にフィンランド、スウェーデンにおいて地下施設閉鎖に関わる計画立案、施工管理、モニタリング、安全評価に携わった実務経験を有する専門家にインタビューを行った。さらに、これらの情報収集・整理結果に基づき、瑞浪超深地層研究所における坑道全体を閉鎖する場合における計画立案や施工管理、モニタリングに関わる考え方や留意事項、さらには坑道埋め戻し技術の開発に関わる試験研究を進めるうえでの留意事項を整理した。

なお、本報告書は原子力機構との契約業務で株式会社ダイヤコンサルタントが実施した諸外国での研究事例のレビューや、専門家へのインタビュー結果を取りまとめたものである。上記契約業務で収集・整理した結果のより詳細な情報については、本報告書の巻末に添付する付録を参照願いたい。

2. 既存情報の収集・整理

瑞浪超深地層研究所と同様に、結晶質岩中に建設された国外の地下研究施設の閉鎖方法およびモニタリング方法に関わる情報の整理を行った。情報収集・整理の対象は、表 2-1 に示す地下研究施設等およびヨーロッパ諸国で共同して行われている坑道閉鎖試験やモニタリングに関わる以下の国際プロジェクトである。

・DOPAS （Full Scale Demonstration of Plugs and Seals）
・LUCOEX （Large Underground Concept Experiments）
・MoDeRn （Monitoring Developments for Safe Repository Operation and Staged Closure）

各地下研究施設、国際プロジェクトごとに収集・整理した情報は、付録 4.2 節に詳述した。

表 2-1 情報収集・整理を行った地下研究施設等

国名	名称・地域	用途
フィンランド	Olkiluoto	高レベル放射性廃棄物処分場
スウェーデン	Forsmark	高レベル放射性廃棄物処分場
スウェーデン	Aspo URL	地下研究施設
カナダ	Canadian URL	地下研究施設
フランス	Cigeo	高・中レベル放射性廃棄物処分場

2.1 坑道閉鎖に関わる要求事項

坑道閉鎖に関わる目的や要請事項は、IAEA（2011）[2]によって以下のように示されている。

・坑道閉鎖の目的は、可能な限り坑道掘削開始前の自然状態に回復させることである。
・坑道閉鎖後の処分場の性能は、初期の設計段階およびセーフティーケースの更新の都度、考慮されるべきである。
・処分場の閉鎖は、地上施設の解体や必要な環境回復を含むべきであり、将来への標識（durable markers）の建設を含むことが望ましい。

フィンランドの Posiva とスウェーデンの SKB は、この目的・要請事項を踏まえて、坑道閉鎖の安全機能（safety functions）として、表 2.1-1 に示す項目を提示している。

処分場あるいは地下研究施設の全体を埋め戻し・閉鎖した事例は世界的に存在しないため、瑞浪超深地層研究所の坑道を埋め戻し・閉鎖する場合は、世界で初めての事例となる可能性がある。したがって、研究開発が進められてきた坑道閉鎖技術を実証する機会として、国際的にも将来の処分坑道閉鎖に役立つ重要な情報が得られることになる。

表 2.1-1　坑道閉鎖に関する安全機能の例

機関および 参考文献	安全機能
フィンランド Posiva Oy (Posiva, 2012)[3]	地表環境、人類・植物・動物の生息域からの長期間の隔離を妨げないように、地下の空間を閉塞しなければならない。
	透水性の高い水みちや地層を塞ぐことによって､人工バリアにとって望ましい予測可能な地球化学条件が形成されるように閉鎖しなければならない。
	処分場への地下水の流入､処分場からの有害物質の放出を制限あるいは遅延させるように閉鎖しなければならない。
スウェーデン SKB (SKB, 2010)[4]	天然バリアの機能を損なうような水みちが､処分場と地表の間に生じないように閉鎖されなければならない。
	閉鎖によってその他のバリア機能を著しく損なうことがあってはならない。
	処分坑道の埋め戻し材料が膨潤したり、移動したりしないように、主坑道は閉鎖されなければならない。
	隣接する坑道や下に位置する坑道の閉鎖性能を損なわないように坑道は閉塞されなければならない。
	斜路や立坑、ボーリング孔は、処分場への予期せぬ侵入を妨げるように閉鎖されなければならない。
	閉鎖は耐久性の高い方法で実施されなければならず､最終処分場で予測される環境においてバリア性能を維持するものでなければならない。

2.2　坑道閉鎖方法（材料，工程）

本節では、収集・整理した情報のうち、坑道閉鎖方法等に関して最も検討が進んでいるフィンランド Olkiluoto の事例を中心に、国外で検討されている坑道閉鎖方法に関する要点を述べる。

フィンランドの処分場建設認可申請中の Posiva は、2.1 節で述べたように坑道閉鎖後の処分場の安全性能は設計段階から考慮されるべきとの考え方から、地下研究施設で実施されたプロジェクトや文献のレビュー（Dixon et al., 2012）[5]を行い、図 2.2-1 に示すように概念的な坑道閉鎖の設計案を示している（Sievänen et al., 2012）[6]。

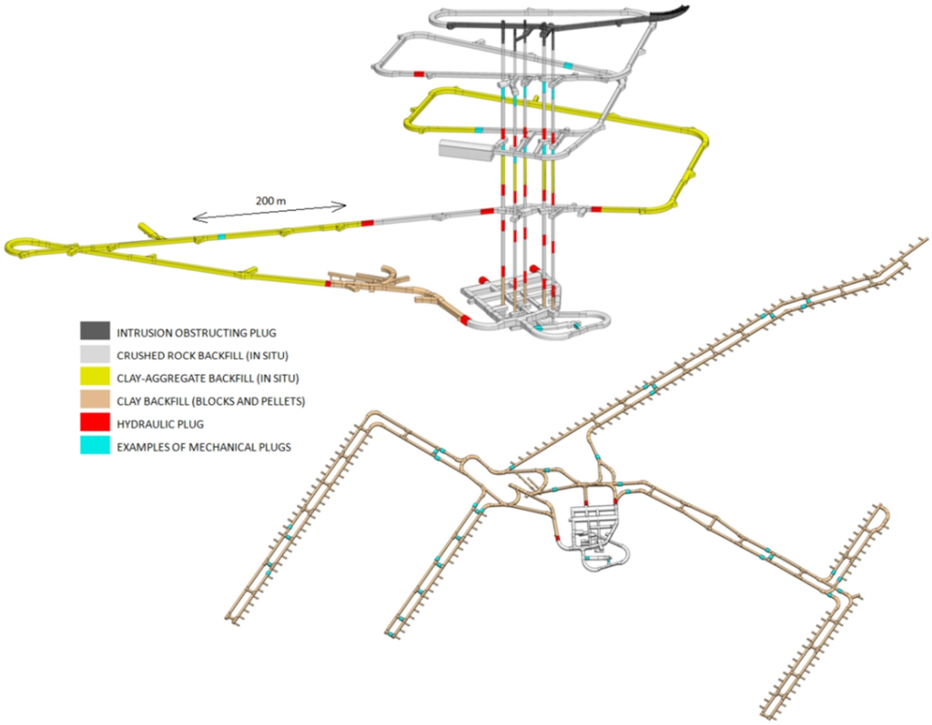

図 2.2-1　フィンランド　Olkiluoto の処分場の坑道閉鎖の設計案（Sievänen et al., 2012）[6)]

上述の坑道閉鎖設計案においては、特に以下の地質環境条件が考慮されている（Sievänen et al., 2012）[6)]。

・割れ目の透水量係数
・母岩の透水係数
・力学的強度
・割れ目帯
・地下水の水質

坑道閉鎖の材料は、プラグと埋め戻し材料から構成される。埋め戻し材料は、周辺の地山との空隙を遮水するために膨潤性材料を含んでいることが一般的である。図 2.2-1 に示した案では、坑道は 3 種類のプラグと 3 種類の埋め戻し材料で閉鎖する設計となっている。

まず、3 種類のプラグについて、Sievänen et al.（2012）[6)]に基づいて、その目的等を以下に整理する。

① 水理プラグ（hydraulic plug）: 図 2.2-2 に示すように、割れ目などが分布し透水性の高い区間と割れ目密度が低く透水性の低い区間の間の地下水の流動を妨げ，水理的に分離することを目的としたプラグである。このプラグは、ストリッパの事例で岩盤内に透水性の高い割れ目が連結している領域に設置した場合、割れ目が地下水の流動経路となり水理プラグの機能を満たせなくなることが示されている。このため、水理プラグは割れ目の分布特性に応じて適切な位置を選定したうえで施工すべきである。

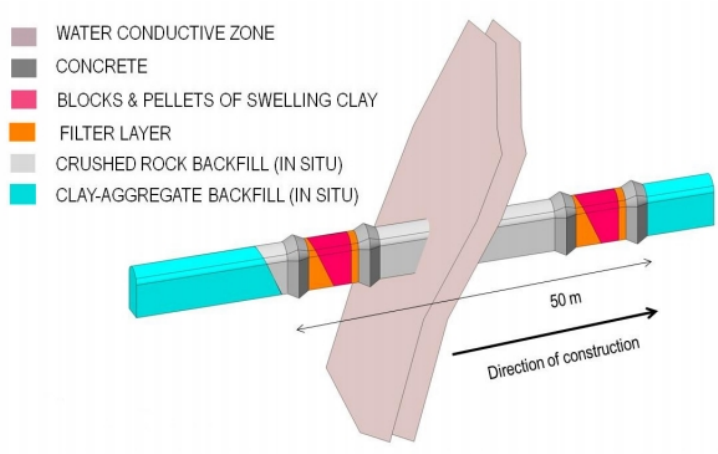

図 2.2-2　水理プラグの例（Dixon et al., 2012）[5)]

② 構造プラグ（mechanical plug）：図 2.2-3 に例を示すように、異なる埋め戻し材料の境界部分に施工され、埋め戻し材料の移動を防ぐことを目的としたプラグである。あるいは、埋め戻し材料が充填された坑道と未充填の坑道の境界部に施工され、坑道閉鎖を効率的に進めることを目的としたプラグである。後者の場合には、長期的な性能は期待されない。

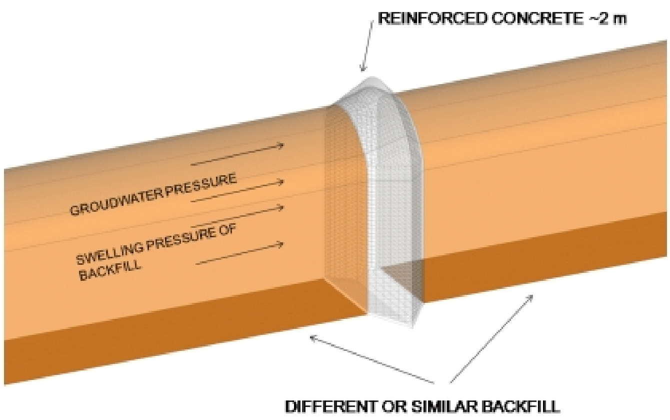

図 2.2-3　構造プラグの例（Dixon et al., 2012）[5)]

③ 侵入防止プラグ（intrusion obstruction plug）：地表近くにおいて、意図しない施設への人間侵入を防ぐことを目的としたプラグである。

材料の選定にあたっては、坑道の湧水量と水質等に基づいて要求される性能に対して、埋め戻し材料の膨潤性と透水性を適切に対応させることが最も重要である（Dixon et al., 2012）[5)]。

充填方法は、埋め戻し材料を原位置で所定の密度に締め固める方法（in situ compaction）とあらかじめ締め固められたブロックを定置し隙間をペレットで充填する方法（blocks and pellets）がある。前者の方法は、後者の方法に比べると埋め戻し材料の沈下が生じやすいことに注意が必要である。この点は、スウェーデンのエスポで実施された BPT（Backfill and Plug Test）で実証されており、図 2.2-4 に示すように、坑道頂部の埋め戻し材料に膨潤性の高いベントナイトを用いる方法が比較対象として提案されている。

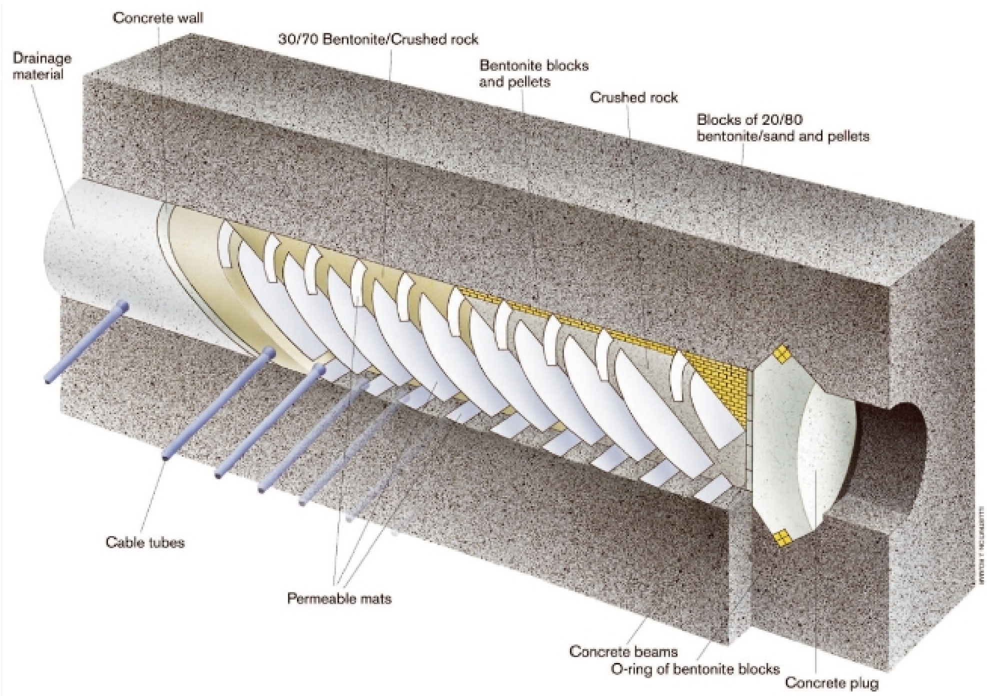

図 2.2-4　エスポで実施された BPT（Backfill and Plug Test）の概念図（SKB, 2010b）[7)]

国外専門家によれば､坑道閉鎖方法に関して､ここまでに述べた事項以外に留意すべき事項は、外来材料（foreign materials）の排除と坑道閉鎖の品質保証である。

外来材料とは、坑道建設に伴って坑道内に持ち込まれた材料であり、自然状態に戻すことを坑道閉鎖の目的とした場合には、坑道閉鎖時にはできるだけ排除する必要がある。これを踏まえてフィンランドの Olukiloto では、以下のように特別な注意が払われている。

・施工段階で使用して良い材料と、使用が禁止される材料の区分が明確にされている。
・設計・施工段階から、コンクリート構造は閉鎖時に取り除くことが想定されている（吹付けコンクリートも同様であるが、作業員の安全上の理由で残される場所がある）。
・すべての有機材料（プラスチック等）は取り除く。
・ロックボルトは必要な場所だけ残す。

埋め戻しとプラグ建設に関する品質保証についても、現在多くの国で議論されている。坑道規模が大きいほど、大量の材料が使われるため、より厳しい品質保証が求められる。

また、坑道閉鎖に関わる工程に関してはあまり情報が無いものの、埋め戻す体積が膨大であることを踏まえると、実際の処分場の埋め戻しには数年を要すると予測される。

2.3　坑道閉鎖に関わるモニタリング

坑道閉鎖に関しては、サイトのモニタリング（site monitoring）だけではなく、プラグや埋め戻し材料等の閉鎖性能のモニタリング（closure performance monitoring）も重要であるとされている。

サイトの水理・地球化学モニタリングは、坑道が閉鎖されたとしても、ボーリング孔を利用して比較的容易に継続することができるため問題は少ない。

これに対して、閉鎖性能のモニタリングは、閉鎖後に坑道にアクセスできないので適用可能なモニタリング方法が限られる。このプラグや埋め戻し材料のモニタリングでは、有線のモニタリ

ングシステムは望ましくないため、無線モニタリングシステムがスイスのグリムゼルで実施された FEBEX（Full-scale Engineered Barriers Experiment）やエスポで実施されている MPT（Multi Purpose Test）で適用されているものの技術的な課題が多い。瑞浪超深地層研究所で埋め戻し材中のモニタリングを行う場合は、純粋な研究施設であるため有線のモニタリングシステムもひとつの選択肢と考えられる。

いずれにしても、モニタリングシステムは、その設置時点で技術的課題が解決されているべきであり、得られる結果と投資費用を踏まえてモニタリングすべきである。坑道閉鎖に関わるモニタリングをいつまで継続すべきか、に関する具体的な情報はほとんど無いが、Posiva ではモニタリングが必要でなくなる時までとしており、モニタリングシステムの寿命のような技術的な理由では決まらないとしている。

モニタリングプログラムの開発については、MoDeRn（Monitoring Developments for Safe Repository Operation and Staged Closure）という国際プロジェクトによって、図 2.3-1 に示すようなワークフローが提案されている。

フィンランドでも、このワークフローに沿ってモニタリング計画が立案されており、最初にモニタリングの目的が次のように設定されている（Posiva, 2012）[8]。

- 環境影響の把握
- 施工による地下および地表環境への影響を踏まえた設計・施工へのフィードバック
- 長期間の安全性の実証 : 処分場周辺の環境条件が長期間にわたって、望ましい条件に保たれていることを実証する。
- サイトの特性理解と既往モデルへのフィードバック : 様々なモデルを確認・実証するためにデータを取得し、サイトとその変化に関する理解を深める。
- 人工バリアの性能監視 : 人工バリアシステムの性能が予測した通りであることを確認する。
- 放射線と放射性物質のモニタリング : 処分場周辺環境における放射線と放射性物質の放出に関するモニタリング。

具体的なモニタリング計画については、付録 Table 7 を参照されたい。

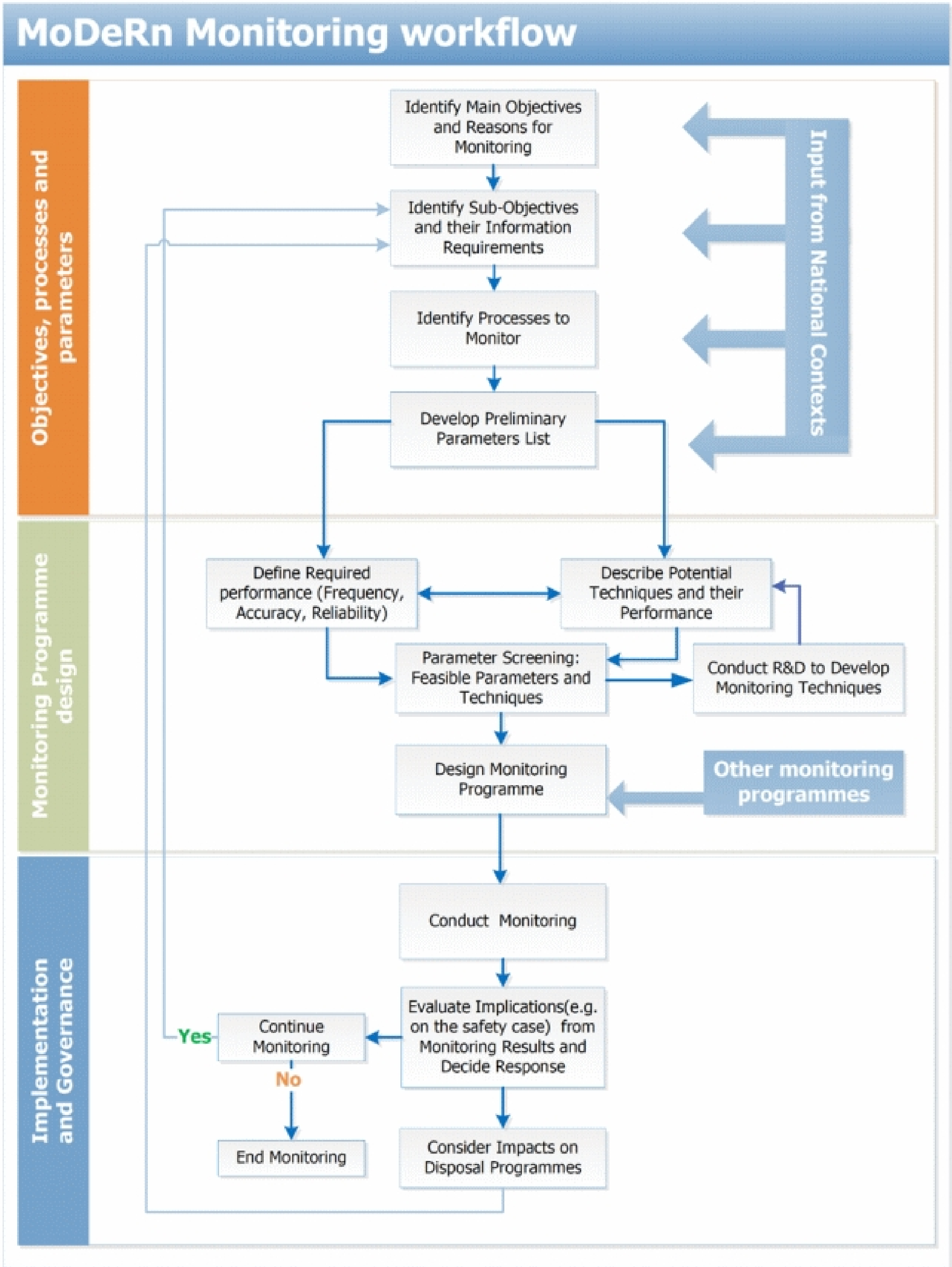

図 2.3-1　国際プロジェクト MoDeRn におけるモニタリング・ワークフロー（White, 2014）[9)]

3. 専門家，実務者へのインタビュー

主にフィンランド、スウェーデン等において地下施設閉鎖に関わる計画立案、施工管理、モニタリング、セーフティアセスメントに携わった実務経験を有する専門家（国外専門家）へのインタビューを通して、瑞浪超深地層研究所で得られている知見も踏まえて議論を行い、計画立案や施工管理、モニタリングに関わる失敗事例や留意事項等の整理を行った。

インタビューは、フィンランド ONKALO での実務経験を有する Saanio & Riekkola Oy の技術者を対象に実施した。なお、インタビューでは瑞浪超深地層研究所の深度 500m と深度 300m の坑道の視察も実施し、瑞浪地域の地質環境条件に応じた坑道閉鎖の考え方等について議論した。

瑞浪超深地層研究所で得られている知見に関して、坑道閉鎖に関わる検討にフィードバックすべき事項を国外専門家が指摘（付録の 3.6 節参照）しているので、その要点を以下に示す。

- 瑞浪超深地層研究所で得られている知見のうち、坑道閉鎖について検討するにあたり考慮が必要な地質学的特徴は以下の通りである。
  - ・水平方向の地質構造（堆積岩と結晶質岩）
  - ・割れ目の密度とそれに伴う湧水
  - ・断層構造およびその他の割れ目帯と透水性の関係
  - ・地下水の水質（地球化学的境界条件）
  - ・地震動、力学特性
- これらをどの程度まで考慮すべきかは、坑道閉鎖の要求事項（目標）に依存する。
- 地質学的特徴に加えて、使用したセメントの量やその他の建設材料もサイトに影響を及ぼしている。例えば、現存している吹付けコンクリートを閉鎖前に完全に取り除くことができないため、モニタリングにおいてはこの影響を考慮して計画する必要がある。
- 瑞浪超深地層研究所では、結晶質岩と堆積岩の 2 種類の地質を対象とすることができるため、異なる地質における閉鎖方法（例えば、立坑のプラグの施工）についても比較が可能である。同じ結晶質岩でも坑道の位置によって地質学的特徴が異なるので、この点においても比較検討が可能である。
- 一方、地質学的特徴はプラグの建設や埋め戻し作業そのものにも影響を及ぼす。例えば、湧水量が多いと作業条件が悪化して、いくつかの小規模な実証試験ができなくなる可能性もある。

国外の地下研究施設等の閉鎖方法およびモニタリング方法に関して、瑞浪超深地層研究所の坑道閉鎖計画にフィードバックすべき事項を国外専門家が指摘（付録の 4.6 節参照）しているので、その要点を以下に示す。

- 瑞浪超深地層研究所の閉鎖に関わる検討は、地質学的および水理地質学的条件に基づいて行われるべきである。具体的には、
  - ・閉鎖概念と閉鎖材料の選定においては、水理地質学的な特徴を、主たる判断基準とする必要がある。
  - ・坑道閉鎖における要求事項と、その他の地質環境条件を設定する必要がある。
  - ・閉鎖時の瑞浪超深地層研究所を活用した研究テーマを特定する必要がある。
- サイトのモニタリングと埋め戻し性能のモニタリングの両方を計画に含むべきである。
- 処分場の閉鎖を実証するような計画とすべきである。同時に、研究所を社会的に安全に閉鎖する計画とすべきである。
- 実規模の地下研究施設の完全閉鎖としては世界で初めての事例であり、間違いなく国際的な

関心が寄せられるので、瑞浪超深地層研究所を活用した国際的な研究テーマが掲げられるべきである。

- 設計と施工に際しては、時間の制約が大きいので、概ね妥当性が裏付けられた施工技術を採用することを推奨する。しかし、工程が許すようであれば、限られた範囲でも試験を行うことが有効である。
- 品質保証方法を開発し、実際に適用すべきである。

4. 瑞浪超深地層研究所の坑道閉鎖，モニタリングに関わる検討事項の整理

第 2 章と第 3 章で整理した情報に基づき、瑞浪超深地層研究所の坑道閉鎖や、それに関わるモニタリングに関わる検討事項を整理した。

4.1 坑道閉鎖時に満たすべき条件

坑道閉鎖に関わる検討を実施するにあたり、以下に記す点を坑道閉鎖時・後に達成すべき目標として設定した。

①瑞浪超深地層研究所の地質環境条件を考慮して、信頼性の高い方法で恒久的に地下研究施設を閉鎖すること（4.3 節を参照）

②科学研究に最大限貢献するとともに、処分事業や安全規制に反映可能な知識の蓄積を目的として、坑道閉鎖時にしかできない試験研究（モニタリングを含む）を行うこと（4.4 節と 4.5 節を参照）

③閉鎖後、土地が安全に利用可能にすること

坑道閉鎖方法の検討手順を図 4.1-1 に示す。

上記の達成目標を満たすため、計画立案においては以下の技術仕様を坑道閉鎖の計画に含めることとした。

① 周辺の地質環境特性を可能な限り坑道掘削前の状態に回復させるために、坑道は冠水ではなく埋め戻すこととし、埋め戻し後の透水係数を周辺の岩盤と同程度以下とする。

② 埋め戻し材料は、実際の処分場で想定される材料と同様の性能を有するものを使用する。

③ 埋め戻し材料やプラグのような閉鎖のための構造について、坑道閉鎖性能を把握するためのモニタリングを行う。

④ 坑道と周辺の地下水特性は、閉鎖前から閉鎖後まで継続してモニタリングする。

⑤ 各モニタリングを終えた後でも、閉鎖した坑道は構造として安定したものとする。

⑥ ウランを含む岩石は、掘削された深度に戻すとともに、地表環境から水理的に隔離する。

坑道閉鎖の目的の設定
- 地下研究施設を恒久的に閉鎖する
- 科学研究に最大限貢献する
- 処分事業や安全規制に反映可能な知識を蓄積する

坑道閉鎖に向けた協力体制の構築
- 関係する機関との議論
-予察的な計画と実施可能な選択肢の提示
- 計画へのフィードバック
- ワークショップの開催

坑道閉鎖の定義
- 契約上の取り決め
-目的、工程、納品物、責任に関する合意
-瑞浪超深地層研究所の坑道閉鎖における満たすべき条件の定義

坑道閉鎖の設計
- 詳細設計，　理由付け（実務的、科学的な特徴に関連して）

施工計画
-実験計画 (坑道閉鎖の設計段階から並行して開始しているべき)
- 施工手順とその検証

施工（実施）

報告書作成

図 4.1-1　坑道閉鎖方法の検討手順

4.2　坑道閉鎖にあたって考慮すべき地質・水理的特徴

瑞浪超深地層研究所の坑道閉鎖を検討するにあたり、地質学的、水理地質学的特徴（表 4.2-1）の観点から、主立坑断層、堆積岩、ウランを含む地層（Uranium bearing formation）を考慮する必要があると判断した。一方、S200_13 断層（図 4.2-1 参照）は、これを挟んだ両側での水質や水圧について、有意な差がモニタリングによって確認されていないため、本検討では考慮しないこととした。

表 4.2-1　坑道閉鎖方法を検討するにあたり考慮すべき地質学的、水理地質学的特徴

坑道閉鎖にあたり考慮すべき地質学・水理地質学的特徴	
主立坑断層 （および断層帯）	周辺の花崗岩よりも低透水性の水理的なバリアである。
堆積岩	水理的・地化学的なバリアとして機能するほぼ水平な粘土層を挟む。
ウランを含む地層	地表の環境から隔離する必要がある。

以上の地質学的、水理地質学的特徴に基づいて、満たすべき条件に適合するように、埋め戻し材を充填する場所の特性に適した材料を選定する。主立坑の止水性能を回復し、ウランを含む地層はそれより上部から隔離する。それ以外の箇所も同様に、安全性、費用対効果、長期的性能、満たすべき条件への適合性に基づいて設計する。

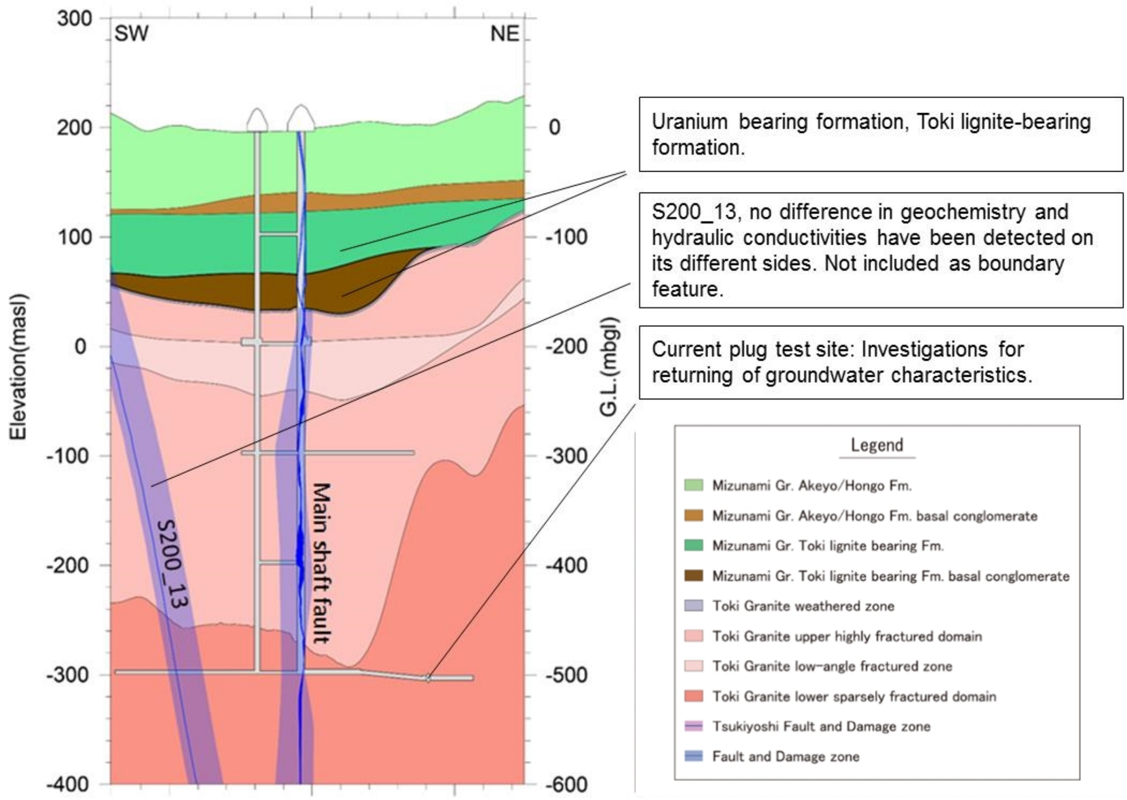

図 4.2-1　瑞浪超深地層研究所を通る鉛直断面と地質学的特徴

4.3　坑道閉鎖方法

坑道閉鎖方法は、4.1 節に述べた達成目標や満たすべき技術仕様と、4.2 節で整理した考慮すべき地質・水理的特徴に基づいて立案する。具体的には、埋め戻しとプラグの 2 つの方法を組み合わせて設計する。坑道閉鎖は主に埋め戻しによって行い、プラグによって埋め戻しに関わる技術仕様を補強する。設計案の一例として 4 種類の埋め戻し材料と 2 種類のプラグを示す。瑞浪超深地層研究所の研究坑道は、地質・水理的特徴に従って、次の 4 つのセクションに分けることができる。これに従って表 4.3-1 に示す 4 種類の埋め戻し材料を利用する案を提案できる（詳細は付録 5.4.3 項参照）。

表 4.3-1　埋め戻し材料の種類と特徴

配置	埋め戻し材料	埋め戻し材料の特徴
主立坑断層帯	低透水性埋め戻し材料 (Tight backfill)	透水性の小さいベントナイトもしくはベントナイトと掘削ズリの混合物
それ以外の結晶質岩	掘削ズリを主とした埋め戻し材料 (Tunnel backfill)	掘削ズリを含む砂、礫
ウランを含む地層	ウランを含む地層からの掘削ズリ (Uranium bearing excavated rock)	ウランを含む地層の掘削ズリ
堆積岩	堆積岩用の埋め戻し材料 (Backfilling for sedimentary rocks)	堆積岩中の地層に応じた埋め戻し材料を選定する。

プラグは、コンクリートプラグと水理プラグの 2 種類が候補として挙げられる。コンクリートプラグは、フィンランドの構造プラグに相当し、異なる埋め戻し材料の境界部に施工され、埋め戻し材料を保持することが目的である。水理プラグは、中間部に止水層（ベントナイト）を挟んだ 2 つのコンクリートプラグによって構成され、坑道方向の地下水流動を抑制することが目的である。この場合のコンクリートプラグは、岩盤損傷領域（EDZ）を横断して施工する。

以上の埋め戻し材料とプラグを用いた坑道閉鎖に関わる設計案の一例として、以下に二つの案を示す。なお、深度 500m に既設の止水プラグについては、閉鎖時・後の試験研究内容に応じて冠水状態で残置する案と埋め戻し材で埋め戻す案が挙げられる。

A 案（図 4.3-1、表 4.3-2）では、
1）主立坑を低透水性の埋め戻し材料で充填する。
2）コンクリートプラグでその埋め戻し材を保持する。
3）両立坑のウラン含有層の下部にコンクリートプラグを打設する。
4）ウランを含む掘削ズリをウランを含む地層の分布深度に埋設する。
5）土岐夾炭累層上部・低透水性層に水理プラグを打設する。
6）水平坑道を掘削ズリを主とした埋め戻し材料で埋め戻す。
7）土岐夾炭累層上部・低透水性層の水理プラグ以浅の埋め戻し材は限定しない。
8）地上部をプラグ打設し、造成する。

B 案（図 4.3-2、表 4.3-3）では、
1）水平坑道と主立坑を遮断する水理プラグを打設する。
2）主立坑断層が主立坑と水平坑道に交わる深度をコンクリートプラグと水理プラグ、低透水性埋め戻し材で閉鎖する。
3）水平坑道を掘削ズリを主とした埋め戻し材料で埋め戻す。
4）両立坑のウラン含有層の下部にコンクリートプラグを打設する。
5）ウランを含む掘削ズリをウランを含む地層の分布深度に埋設する。
6）土岐夾炭累層上部・低透水性層に水理プラグを打設する。
7）土岐夾炭累層上部・低透水性層の水理プラグ以浅の埋め戻し材は限定しない。
8）地上部をプラグ打設し、造成する。

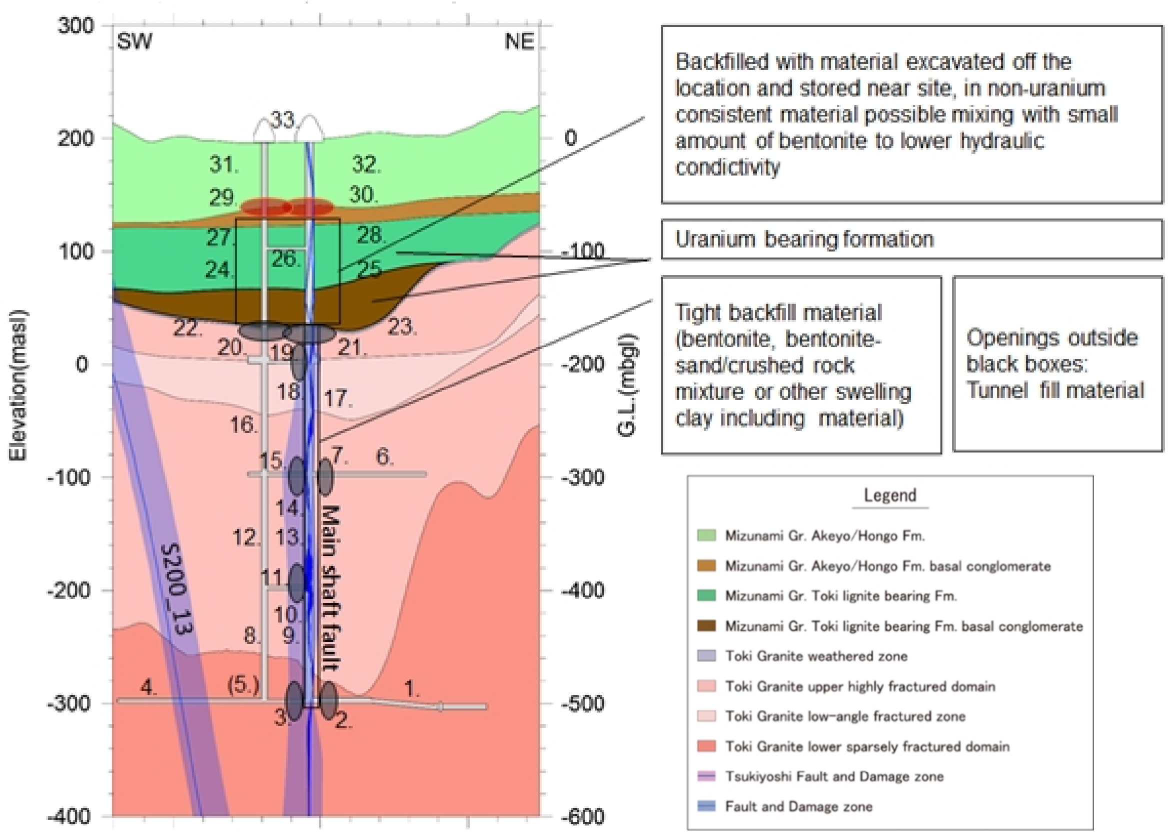

図 4.3-1　瑞浪超深地層研究所の坑道閉鎖の設計案　A 案

表 4.3-2　埋め戻し手順（A 案）（1/2）

手順	位置	項目	深度（m）	埋め戻し材	プラグ
1	坑道	埋め戻し	-500	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
2	水平坑道	プラグ	-500	-	コンクリート構造
3	水平坑道	プラグ	-500	-	コンクリート構造
4	水平坑道	埋め戻し	-500	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
(5)	水平坑道	プラグ試験（付録 5.6.1 項）	-500	-	ベントナイト挟在コンクリート構造
6	水平坑道	埋め戻し	-300	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
7	水平坑道	プラグ	-300	-	コンクリート構造
8	換気立坑	埋め戻し	-500～-400	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
9	ニッチ	埋め戻し	-500～-400	低透水性埋め戻し材料(Tight backfill)	-
10	Gallery	プラグ	-400	-	コンクリート構造

表 4.3-2　埋め戻し手順（A 案）（2/2）

手順	位置	項目	深度（m）	埋め戻し材	プラグ
11	水平坑道	埋め戻し	-400	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
12	換気立坑	埋め戻し	-400	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
13	ニッチ	埋め戻し	-400～-300	低透水性埋め戻し材料(Tight backfill)	-
14	水平坑道	プラグ	-300	-	コンクリート構造
15	水平坑道	埋め戻し	-300	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
16	換気立坑	埋め戻し	-300～-200	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
17	ニッチ	埋め戻し	-300～-200	低透水性埋め戻し材料(Tight backfill)	-
18	水平坑道	プラグ	-200	-	コンクリート構造
19	水平坑道	埋め戻し	-200	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
20	換気立坑	埋め戻し	-200～-170	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
21	ニッチ	埋め戻し	-200～-170	低透水性埋め戻し材料(Tight backfill)	-
22	換気立坑	プラグ	-170	-	コンクリート構造
23	ニッチ	プラグ	-170	-	コンクリート構造
24	換気立坑	埋め戻し	-170～-100	当該深度の掘削ズリ	-
25	ニッチ	埋め戻し	-170～-100	当該深度の掘削ズリ	-
26	水平坑道	埋め戻し	-100	当該深度の掘削ズリ	-
27	換気立坑	埋め戻し	-100～-70	当該深度の掘削ズリとベントナイトの混合物	-
28	ニッチ	埋め戻し	-100～-70	当該深度の掘削ズリとベントナイトの混合物	-
29	換気立坑	止水プラグ	キャップロック	-	ベントナイト挟在コンクリート構造
30	ニッチ	止水プラグ	キャップロック	-	ベントナイト挟在コンクリート構造
31	換気立坑	埋め戻し	キャップロック～地上	当該深度の掘削ズリとベントナイトの混合物	-
32	ニッチ	埋め戻し	キャップロック～地上	当該深度の掘削ズリとベントナイトの混合物	-
33	地上	プラグ打設と表土造成	0	-	コンクリート構造

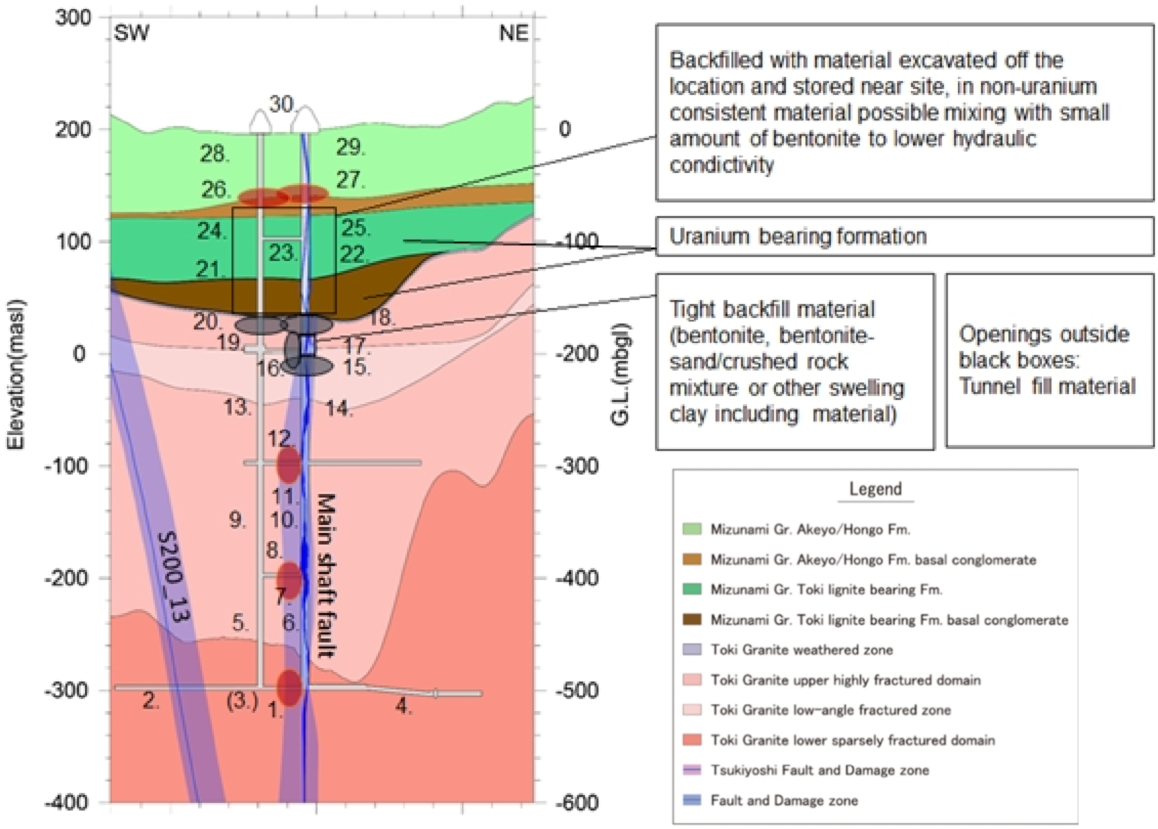

図 4.3-2　瑞浪超深地層研究所の坑道閉鎖の設計案　B 案

表 4.3-3　埋め戻し手順（B 案）（1/2）

手順	位置	項目	深度（m）	埋め戻し材	プラグ
1	水平坑道	プラグ	-500	-	ベントナイト挟在コンクリート構造
2	水平坑道	埋め戻し	-500	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
(3)	水平坑道	プラグ試験 （付録 5.6.1 項）	-500	-	ベントナイト挟在コンクリート構造
4	水平坑道	埋め戻し	-500	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
5	換気立坑	埋め戻し	-500～-400	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
6	ニッチ	埋め戻し	-500～-400	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
7	水平坑道	止水プラグ	-400	-	ベントナイト挟在コンクリート構造
8	水平坑道	埋め戻し	-400	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-

表 4.3-3　埋め戻し手順（B 案）（2/2）

手順	位置	項目	深度（m）	埋め戻し材	プラグ
9	換気立坑	埋め戻し	-400～-300	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
10	ニッチ	埋め戻し	-400～-300	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
11	水平坑道	止水プラグ	-300	-	ベントナイト挟在コンクリート構造
12	水平坑道	埋め戻し	-300	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
13	換気立坑	埋め戻し	-300～-200	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
14	ニッチ	埋め戻し	-300～-220	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
15	ニッチ	プラグ	-220		コンクリート構造
16	水平坑道	プラグ	-200		コンクリート構造
17	ニッチ/水平坑道	埋め戻し	-200	低透水性埋め戻し材料	
18	ニッチ	プラグ	-180	-	コンクリート構造
19	水平坑道 & shaft	埋め戻し	-200～-170	掘削ズリを主とした埋め戻し材料（Tunnel backfill）	-
20	換気立坑	プラグ	-170	-	コンクリート構造
21	換気立坑	埋め戻し	-170～-100	当該深度の掘削ズリ	-
22	ニッチ	埋め戻し	-170～-100	当該深度の掘削ズリ	-
23	水平坑道	埋め戻し	-100	当該深度の掘削ズリ	
24	換気立坑	埋め戻し	-100～-70	当該深度の掘削ズリ	-
25	ニッチ	埋め戻し	-100～-70	当該深度の掘削ズリ	-
26	換気立坑	止水プラグ	キャップロック	-	ベントナイト挟在コンクリート構造
27	ニッチ	止水プラグ	キャップロック	-	ベントナイト挟在コンクリート構造
28	換気立坑	埋め戻し	キャップロック～地上	当該深度の掘削ズリとベントナイトの混合物	-
29	ニッチ	埋め戻し	キャップロック～地上	当該深度の掘削ズリとベントナイトの混合物	-
30	地上	プラグ打設と表土造成	0	-	コンクリート構造ほか

坑道閉鎖の設計案として原子力機構内で事前に予備検討して国外専門家に提示した案（図 4.3-3）では、水理地質構造と水平坑道のレイアウトに基づいて止水プラグを配置している。国外専門家が提案した 2 案とともに表 4.3-4 で比較する。原子力機構案に対する国外専門家の意見は、以下の通りである。

・　水平坑道に低透水性埋め戻し材料を充填するため膨潤性材料の使用量が多くなり過ぎ、掘削ズリを充填すると満たすべき条件を満たせなくなることが懸念される。
・　立坑を低透水性材料で埋め戻す場合は、深度 300m の止水性プラグは過剰投資であり、水平坑道の埋め戻しを容易にするためのコンクリートプラグで十分に代用できる。
・　上部高密度割れ目帯と下部低密度割れ目帯の透水性に明確な違いが認められず、元々地下水の水質にも違いがなかったことから、深度 460m 付近のプラグの必要性は低い。
・　水平坑道を、ベントナイト／砂／砕石混合材料で埋め戻す場合は、相対的に周辺岩盤より透水性が低くなるため、粘土材料が流出する。

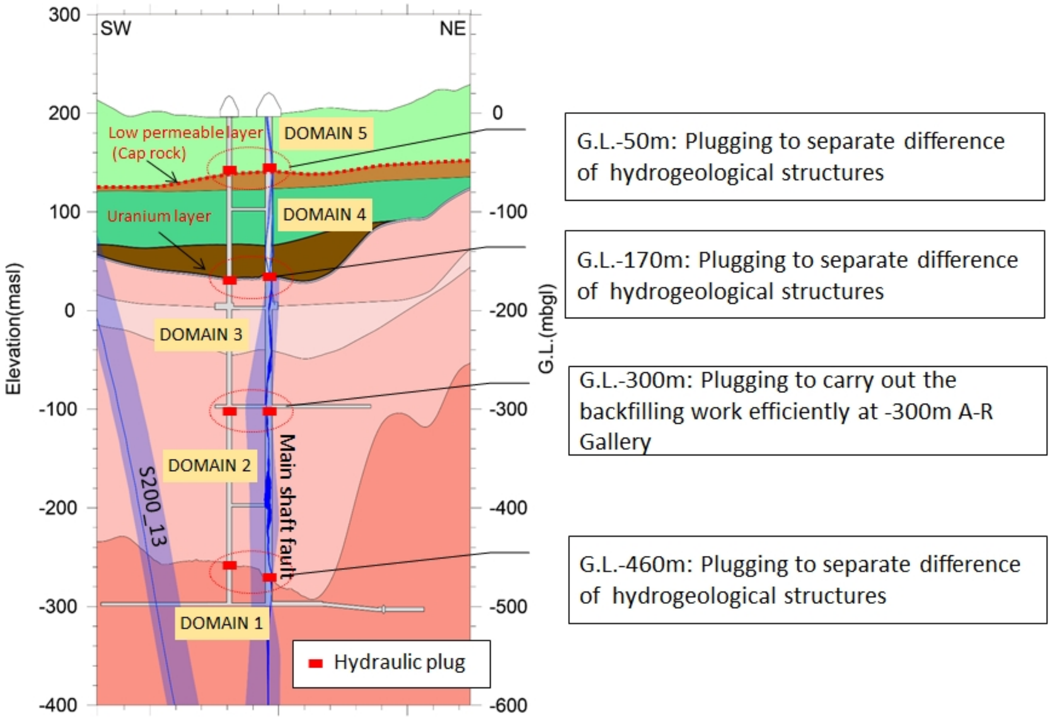

図 4.3-3　瑞浪超深地層研究所の坑道閉鎖の設計案　原子力機構案（Previous alternative）

表 4.3-4　坑道閉鎖の設計案の比較

比較項目	A 案	B 案	原子力機構案
満たすべき条件に対する適合性	良好	良好	限定的
膨潤性材料の使用量（案同士の相対比較）	多い	少ない	多い
コンクリートプラグの数*	12	14	16
うち　水平坑道	4	7	-
うち　立坑	8	7	16
水理プラグの数	2	5	8
うち　水平坑道	-	3	-
うち　立坑	2	2	8

* 水理プラグ 1 つあたり、コンクリートプラグ 2 つとして計算

本報告書では、坑道閉鎖の設計案を示したが、地下研究坑道全体の閉鎖は大きなプロジェクトであり、埋め戻し材料やそのレイアウトだけではなく、実際の施工の観点からも詳細な計画が必要である。瑞浪超深地層研究所では湧水量がかなり多いため、埋め戻し材料を充填しながら建設時に導入された構造を解体・撤去することが最大の困難であると考えられる。

4.4 坑道閉鎖に関するモニタリングとモデリング

坑道閉鎖性能に関わる詳細で十分な情報を得るためには、埋め戻し材だけでなく、それに関連する周辺環境条件の経時変化を把握するためのモニタリングが不可欠である。また、モニタリングは、埋め戻し材や周辺環境条件等の変化に関わる事前予測結果の妥当性を確認するためにも活用できる。

周辺環境条件の変化に関わるモニタリングでは、少なくとも地下水の水質、水圧の観測される必要がある。また、地震計（加速度計）によるモニタリングをしておくことが望ましい。閉鎖性能に関しては、埋め戻し材料の飽和度と膨潤圧の変化を少なくともいくつかの位置でモニタリングする必要がある。

坑道閉鎖に関わる設計や施工計画立案時に、坑道閉鎖に用いる材料の変化や周辺環境条件について、モデリングによる事前予測を行うことが重要である。

なお、モニタリングおよびモデリングの詳細は付録の 5.5 節に示されている。

4.5 坑道閉鎖前または閉鎖時に実施すべき研究課題

科学研究に最大限貢献するために､坑道閉鎖を利用していくつかの実験を行うことが望ましい。国外専門家からは、以下のようなアイデアが示されている。

〇科学的な実験

- 埋め戻し材料の性能試験（コロイドのモニタリング）
- 非膨潤粘土（イライト等）を用いた止水試験
- コンクリートの性能試験

〇工学的な実験

- 施工の品質保証
- モニタリング技術
- 外来材料（吹付けコンクリート等）の排除
- ボーリング孔の閉塞

各実験の詳細は付録の 5.6 節に示されている。一例として、コンクリート性能試験の概念図を図 4.5-1 に示す。この試験は、坑道閉鎖から 5～20 年程度経過後に、立坑のコンクリートライニングに向けてボーリング孔を掘削し、コアとしてコンクリートを回収するものである。掘削したボーリング孔は、コア回収後に再度コンクリートを充填する。

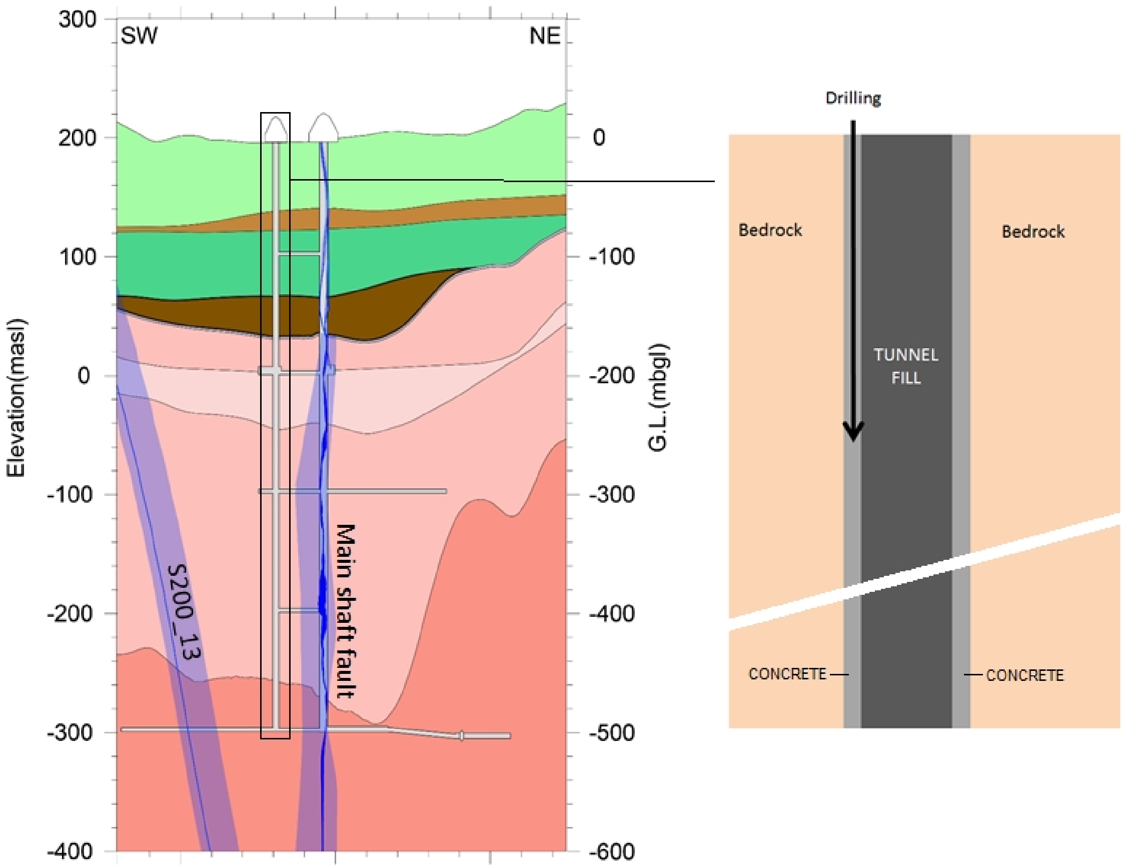

図 4.5-1　コンクリート性能試験の概念図

4.6　スケジュールに関する制約条件

国外専門家から提言された坑道閉鎖のイメージを図 4.6-1 に示す。全体の枠組みは、次のような要素から構成される。なお、詳細な工程は未確定であり、詳細が明確になり次第あらためて検討を行う必要がある。

・第 3 期中期計画期間（2015～2019 年度）における調査研究計画

・サイトのモニタリング段階（現在行われているモニタリングは少なくとも 2022 年 1 月までは継続することが望ましい）。

なお、モニタリングを、土地利用や地域の計画を踏まえて、いつまで継続できるかを明確にすべきである。閉鎖後についても、サイトと閉鎖材料のモニタリングは継続して行うことを推奨する。

坑道全体を閉鎖するための工程についても検討を行った。設計、施工計画、実際の施工に十分な時間を割いておく必要がある。特に、埋め戻し材料の挙動をモニタリングするために、モニタリングシステムを設置し、動作確認をする場合には、適切な密度での埋め戻しを行う等、プラグを施工する時間がより長く必要となる。必要な年数を勘案した概念的なスケジュール案を図 4.6-2 に示す。

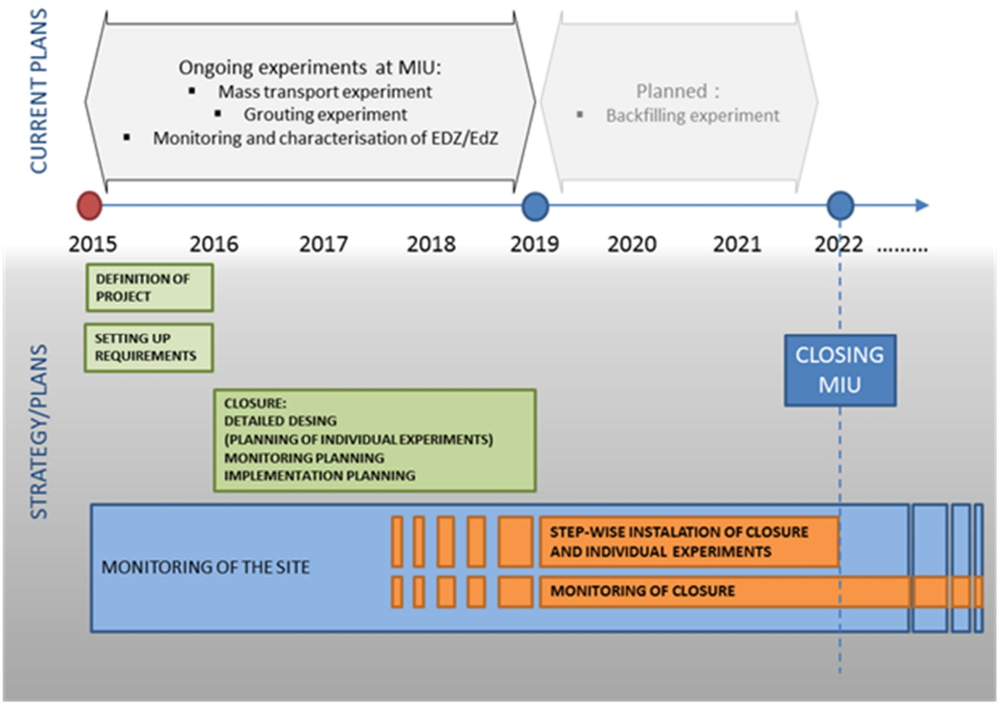

図 4.6-1　坑道閉鎖事業全体の枠組み

検討ステップ（年次）	1	2	3	4	5	6	7	8
坑道閉鎖の目的と前提の設定								
国際的な協力関係の構築 ワークショップ								
坑道閉鎖における満たすべき条件の設定								
坑道閉鎖の全体設計								
モニタリングの計画立案								
坑道閉鎖の施工計画立案								
坑道閉鎖の実施（埋め戻し、プラグ施工）								
坑道閉鎖を利用した研究的実験（4.5 節）の計画立案								
坑道閉鎖を利用した研究的実験（4.5 節）の実施								
閉鎖性能のモニタリング								*
周辺環境条件のモニタリング								*

* モニタリングは坑道閉鎖後も継続すべきである。

図 4.6-2　スケジュールのイメージ

5. まとめ

第 2 章と第 3 章を踏まえて、瑞浪超深地層研究所を対象事例として坑道閉鎖、モニタリングに関わる留意点を前節までに整理した。要点を以下にまとめる。

1) 瑞浪超深地層研究所の施設閉鎖は、地層処分に関わる研究用地下施設の世界最初の全坑道閉鎖事例となる可能性が有る。したがって、世界中の処分関係者から関心が寄せられ、ワークショップや共同研究等を通じた国際的な貢献が期待される。吹付けコンクリートのような坑道建設のために導入された材料の埋め戻し後の挙動、埋め戻し・プラグの品質保証方法等、国際的に議論されている研究テーマを実施する貴重な機会が瑞浪超深地層研究所の研究開発課題として存在する。
2) 瑞浪超深地層研究所の施設閉鎖計画立案にあたっては、次の事項を考慮することが必要である。
   ①施設閉鎖の目的・方針（国際的な要請や地域の要請も含む）
   ②施設閉鎖の設計・計画が満たすべき条件（坑道閉鎖の目的・方針に基づく）
   ③瑞浪超深地層研究所でこれまでに得られている主要な地質・水理・地化学的特徴
   ④国外の地下研究施設で実施されている施設閉鎖に関するプロジェクトの経験
   ⑤フィンランド、スウェーデンの処分場で検討されている施設閉鎖の方法
3) 施設閉鎖の目的に、閉鎖後の安全性と処分関係者への貢献を含むのであれば、本報告書が例示した埋め戻しとプラグによる方法で施設閉鎖は計画されるべきである。埋め戻しとプラグの機能や材料は、埋め戻しあるいはプラグ位置の地質・水理的特徴に応じて選定することが効果的であり、埋め戻し後の閉鎖性能、埋め戻し工程・費用は埋め戻しとプラグの機能・材料選定と配置計画に強く依存する。
4) 技術的観点からは、予測と検証を目的としたモデリングとモニタリングを、坑道閉鎖前に開始し、坑道閉鎖後まで継続することが求められる。地質環境の回復過程の把握を目的とした周辺のモニタリングだけではなく、閉鎖性能を検証することを目的とした埋め戻し材料とプラグのモニタリングも必要となる。
5) 次のような作業は、世界でも初めての試みや、技術的な困難さを含んでおり、十分な時間を確保しておく必要がある。
   ①湧水量が多い坑道での埋め戻しは地下研究施設では例がなく、作業上の困難が予測される。
   ②人工材料を極力残さないように、既設構造物を解体しながら埋め戻し材料を充填する作業も処分分野特有の課題であり、慎重な計画立案と施工が求められる。
   ③閉鎖性能をモニタリングするための機器設置においては、埋め戻し、プラグ施工にも慎重さが要求され、動作確認と合わせて長い期間が必要となる可能性がある。

以下に国外専門家のレポート（付録）の Summary の日本語訳を示す。まとめの他に国外専門家の意見・提言が含まれている。閉鎖方針に基づいて閉鎖計画を構築するまでの流れを図 5-1 に示す。

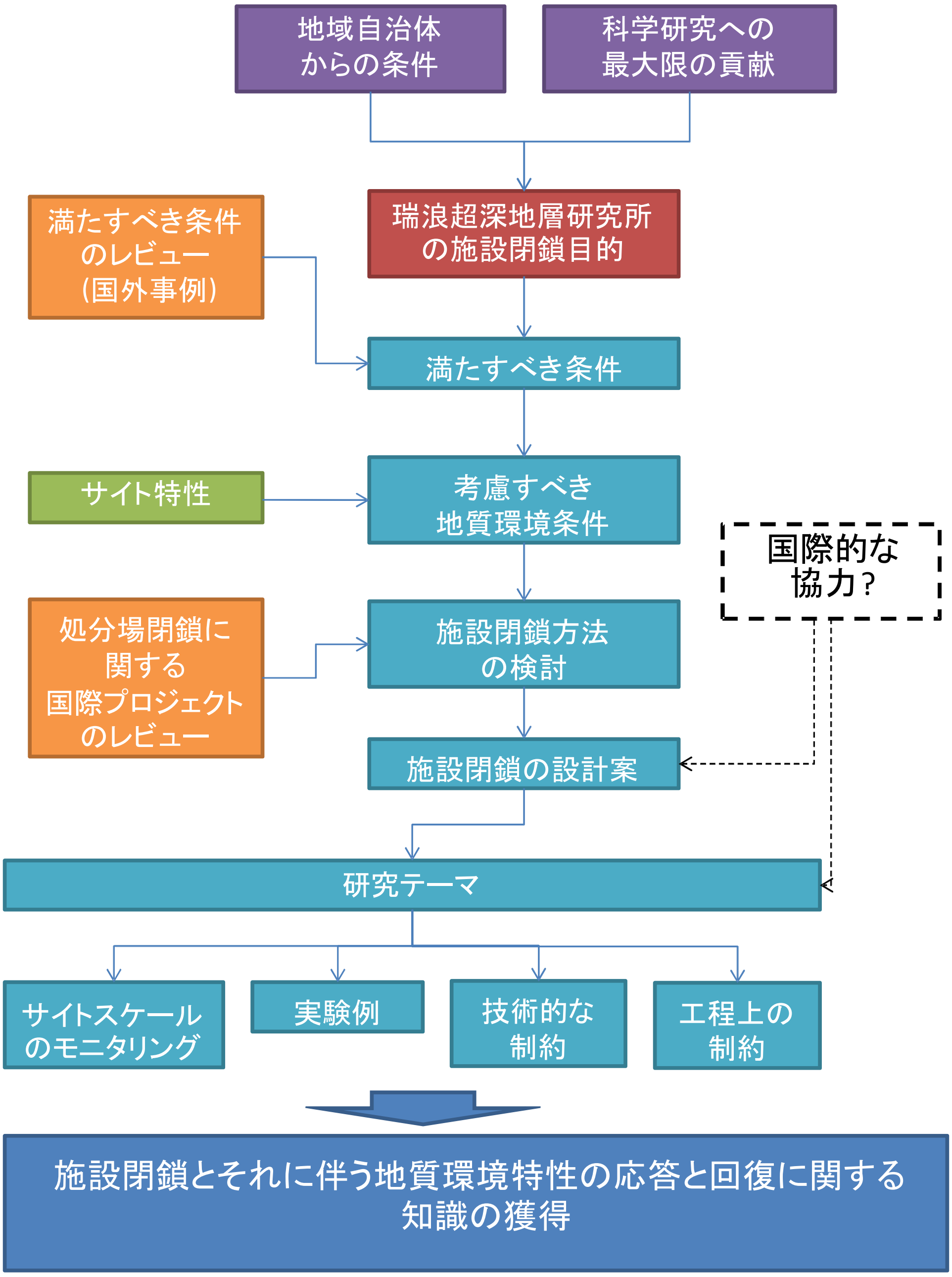

図 5-1　閉鎖方針の立て方と計画の進め方

瑞浪超深地層研究所の閉鎖では、地下施設を対象としたフルスケールの試験と検証ができる。地層処分分野では、フルスケールの施設閉鎖試験の事例はなく、フルスケールのモニタリングと合わせて操業段階と埋め戻し後の諸課題に関わる知見を得ることが可能になる。また、モデルの構築に必要なデータ取得も目的とすることができる。サイトスケールの環境修復というトピックは、フルケースで今日までほとんど研究されていない科学研究テーマである（図 5-2）。

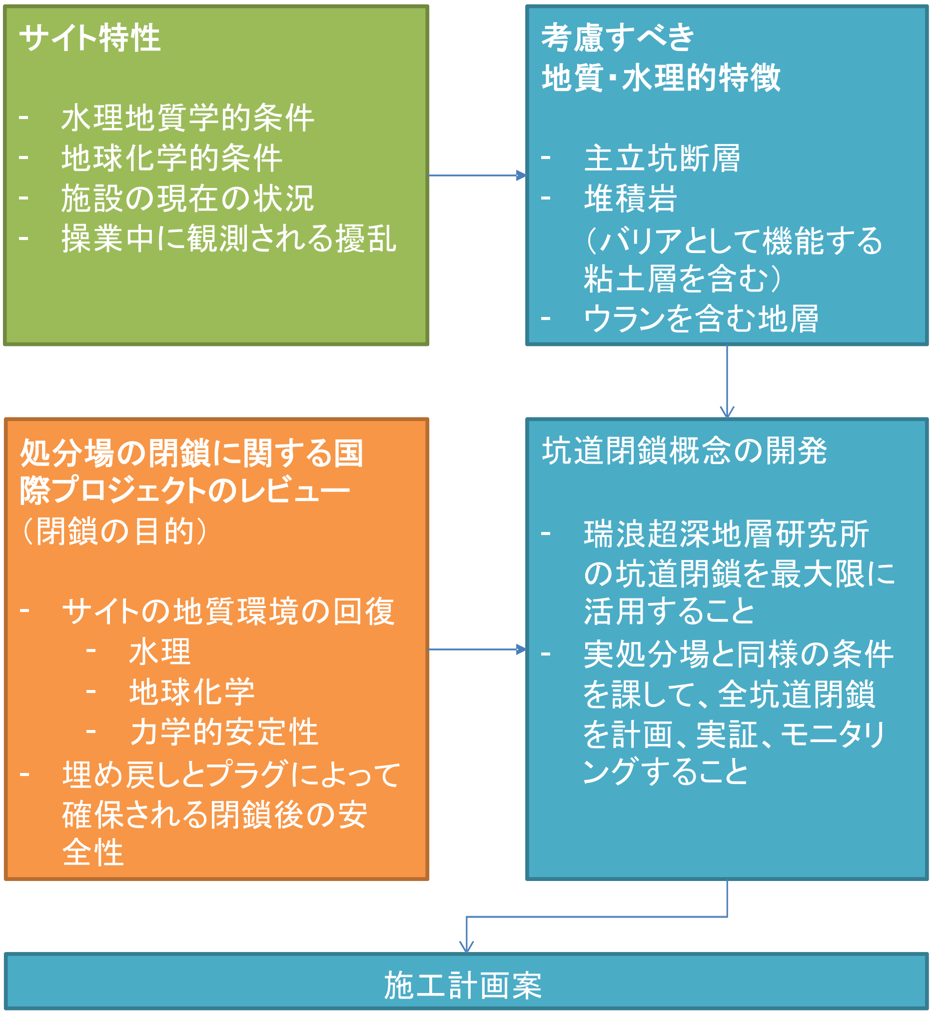

図 5-2　国際的な経験とサイトの地質環境特性を反映した坑道閉鎖方法の構築の考え方

本報告書が提案している計画は、科学的に最適なものを目指しており、予算や詳しいスケジュールのような実現のための制約条件については、詳しくは述べていない。ただし、計画がフルスケールであることを反映して、瑞浪超深地層研究所の閉鎖が持つ可能性を最大限に利用するためには、国際的な協力が極めて重要と考えられる。

現時点で予定されている瑞浪超深地層研究所のスケジュールでは、再取り出しを伴う大規模実験は長い時間を要するので不可能である。このことを反映して、計画では埋め戻し中に計測可能な実験を含む段階的な埋め戻しに重点を置いている。また、地上からの長期間のモニタリングを含む計画としている。

設計、施工、モニタリングの経験に加えて、閉鎖後の初期状態を明確にするために、埋め戻しの品質保証方法についてもこのプロジェクトを通じて開発すべきである。

実際の処分場であれば問題が大きいと考えられる、多量の湧水あるいは広範囲の吹付けコンクリート等の瑞浪超深地層研究所の特徴も、坑道閉鎖のデモンストレーションと考えれば有効である。特に、多量の湧水は埋め戻し材料をより早く飽和させ、広範囲のセメントのモニタリングは普通ポルトランドセメントを含むシステムの重要な例として利用することができる。

また、浅い深度の坑道からは中低レベル廃棄物処分場に役立つ情報が得られることが期待される。特に、土岐花崗岩を覆う堆積岩のキャップロックは埋め戻しの設計に考慮され、堆積岩の処

分場の閉鎖に役立つ情報を提供してくれるものと期待される。このことは、処分母岩として堆積岩を考えている機関や浅深度処分を考えている機関からも関心を得るための鍵となる可能性がある。

フルスケールでの坑道閉鎖の実証は国際的にも挑戦的なプロジェクトと考えられるため、全体計画は地層処分全般に貢献するものであるべきである。坑道閉鎖のデモンストレーションの主目的は以下の通りである。

・結晶質岩と堆積岩の両方に対して、処分場の閉鎖方法を適用し、モニタリングすることによって、あらゆる深度の地層処分に適用可能な坑道閉鎖に関する情報を得ること。

全体計画は、次のように細分して考えることができる。

・設計と施工
・品質管理と品質保証
・モニタリング
・坑道閉鎖の長期的な安全性の実証
・モデリング

瑞浪超深地層研究所の閉鎖では、実際の処分場のような長期性能は必要とされないが、放射性廃棄物処分研究に貢献できる坑道閉鎖の実証計画のためには、長期性能は考慮すべきトピックであり、最終的な計画や目的は、これらによって変わってくる。最近のすべての高レベル放射性廃棄物処分プログラムにおいては、閉鎖は処分システムの一部と捉えられている。Posiva と SKB は、長期安全評価の一部として閉鎖性能を評価しており、世界中のすべてのプロジェクトでも同様である。瑞浪超深地層研究所の閉鎖は、日本の放射性廃棄物処分プログラムに貴重な情報を与えるだけではなく、国際的にも貴重な情報を与えることができるプロジェクトである。

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付録　フィンランドを対象とした情報収集結果

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STRATEGY FOR CLOSING MIZUNAMI UNDERGROUND ROCK LABORATORY

CONTENTS

ABSTRACT 33
1 INTRODUCTION 38
1.1 Background 38
1.2 Current status of MIU 39
1.3 Scope of the work 42
2 Description of underground openings and drill holes 43
3 Description of the MIU site 48
3.1 Geological setting 48
3.2 Groundwater system 51
3.3 Groundwater chemistry 54
3.3.1 Baseline conditions 54
3.3.2 Long-term evolution of the groundwater system 56
3.4 Stress state and mechanical properties of rock 57
3.5 Effects of excavation and operation 58
3.6 Feedback for MIU closure 59
4 Review of projects for closing tunnels and monitoring restoration 60
4.1 Constraints of closing tunnels 60
4.1.1 General requirements 60
4.1.2 Safety functions in deep geological disposal projects 62
4.2 Review of selected closing projects 62
4.2.1 Spent nuclear fuel repository at Olkiluoto, Finland (including ONKALO Underground Rock Characterisation Facility) 63
4.2.2 Spent nuclear fuel repository, Forsmark, Sweden 67
4.2.3 Äspö URL Sweden 70
4.2.4 Canada URL 72
4.2.5 Cigéo Repository, France 74
4.2.6 DOPAS 75
4.2.7 LUCOEX 78
4.2.8 MoDeRn 79
4.2.9 Other disposal projects 81
4.3 Geological and hydrogeological/chemical conditions around tunnels 81
4.4 Closure production 83
4.5 Monitoring of closure 86
4.6 Feedback for MIU closure 88
5 Strategy and plans for closing the Mizunami URL 91
5.1 Strategy 91
5.2 Requirements 92
5.3 Boundary conditions and AIMS 93
5.4 Closure concept development 95
5.4.1 MIU closure backfill 95
5.4.2 MIU closure plugs 97
5.4.3 MIU closure design alternatives 97
5.4.4 Previous closure design and discussion 105
5.4.5 Comparison of alternatives 108
5.5 Site scale monitoring and modelling 109

5.5.1 Monitoring 109
5.5.2 Modelling 110
5.6 Experiments 110
5.6.1 Backfill erosion experiment 111
5.6.2 Non-swelling clay test for sealing purposes (illite) 112
5.6.3 Concrete performance experiment 112
5.6.4 Installation, initial state and QA 113
5.6.5 Monitoring experiments 114
5.6.6 Removal of foreign materials 114
5.6.7 Borehole sealing experiment 115
5.7 Technical challenges 116
5.8 Schedule constraints 117
6 Summary 120
References 123

ABSTRACT

In order to make the most of the underground rock laboratory's (URL) operational time, a strategy for closing the facility has been developed. The strategy aims:

- to provide a solution to close the MIU in a way that it is physically and environmentally safe
- to provide valuable information for the radioactive waste management (RWM) on the closing geological repositories by employing a strategy that aims at restoring the geological conditions on site.

These aims go hand in hand, since the effective closure includes both of these aspects inherently. The overall approach taken is illustrated in Figure A1.

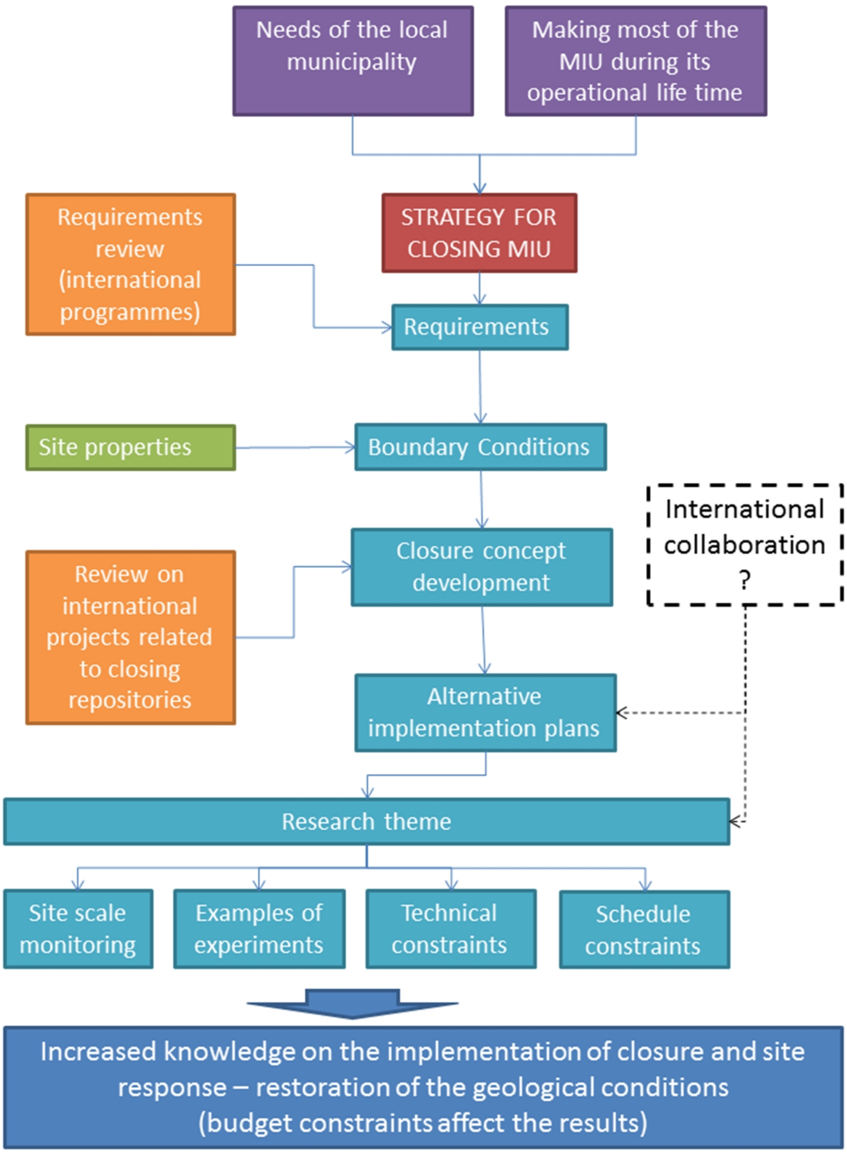


Figure A1. Schematic presentation of the approach taken to develop strategy and implementation plans for JAEA.

The strategy is further developed by establishing preliminary requirements for the closure. These are based on the information available from disposal programmes internationally. Requirements include also the input that is used to write out the strategy. Requirements are then used to develop an implementation plan. In order to set boundary conditions for preliminary design, site properties affecting the local geology, hydrogeology and Hydrogeochemistry have been reviewed. These boundary conditions include features that need to be accounted for in order to fulfil the requirements (see Figure A2). These include for example hydrogeological barriers, e.g. the main shaft fault, and differences in hydrological conductivities in different sections of the facility.

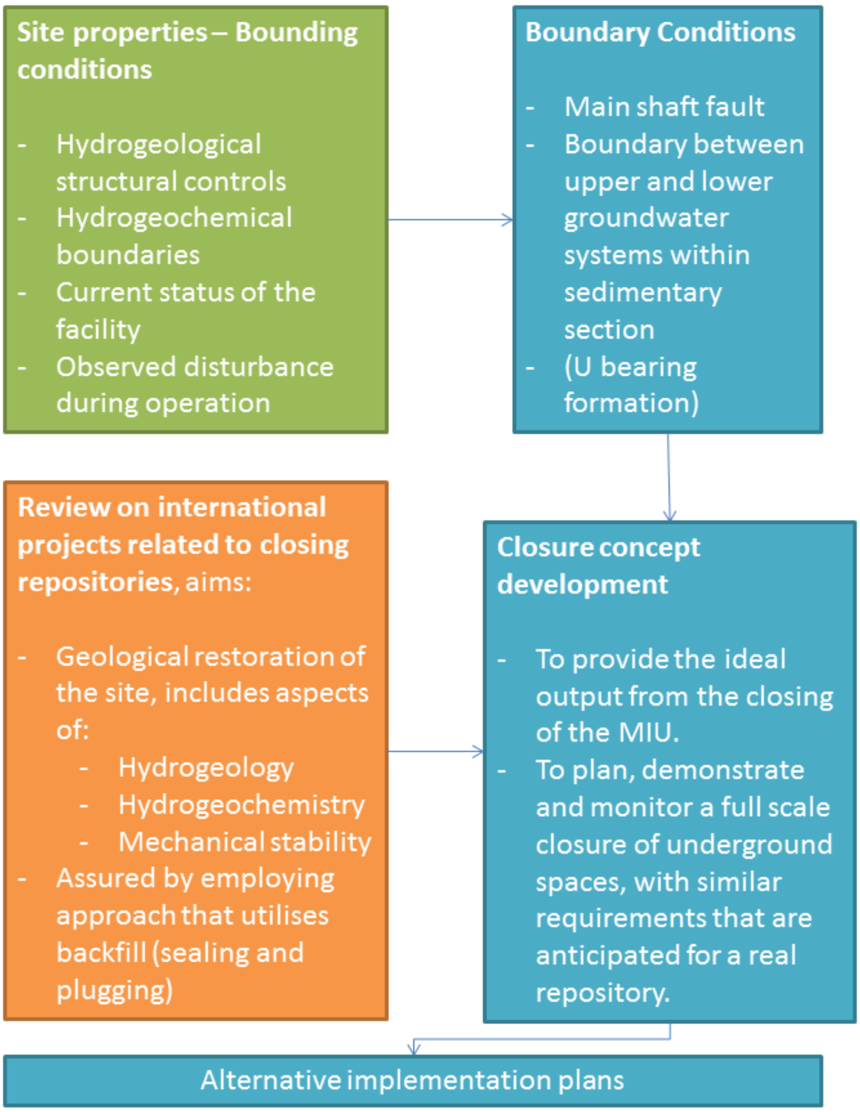


Figure A2. Derivation of boundary conditions and development of closure concept.

Closure concept development (Figure 2) has been presented by producing alternative approaches to actually implement the closure. For this plan, the review of the international state-of-the-art research and development in relation to closure have been utilised and potential of MIU closure has been screened against the overall need within the field of geological disposal of radioactive wastes.

Two alternative designs for MIU closure are presented in this report. Both alternatives comply with the initial requirements considered in this report, and they utilise different backfill and plug types to produce an efficient and safe solution. Closure design alternative A is presented in Figure A3 and closure design alternative design B in Figure A4. Both alternatives suggest rock material backfill for most of the URL volumes and return of original host rock to Toki lignite-bearing formation. In alternative A the design has a smaller quantity of plugs but more extensive use of tight backfill in main shaft. In alternative B the volume of tight backfill is very low, limited only to act as hydraulic seals between concrete plugs where the main shaft fault has been intersected with URL openings, but there are more plugging structures. A closure design drafted earlier is also presented in this report, but as such it would not comply with the requirements and thus modification, or use of alternative A or B is advisable.

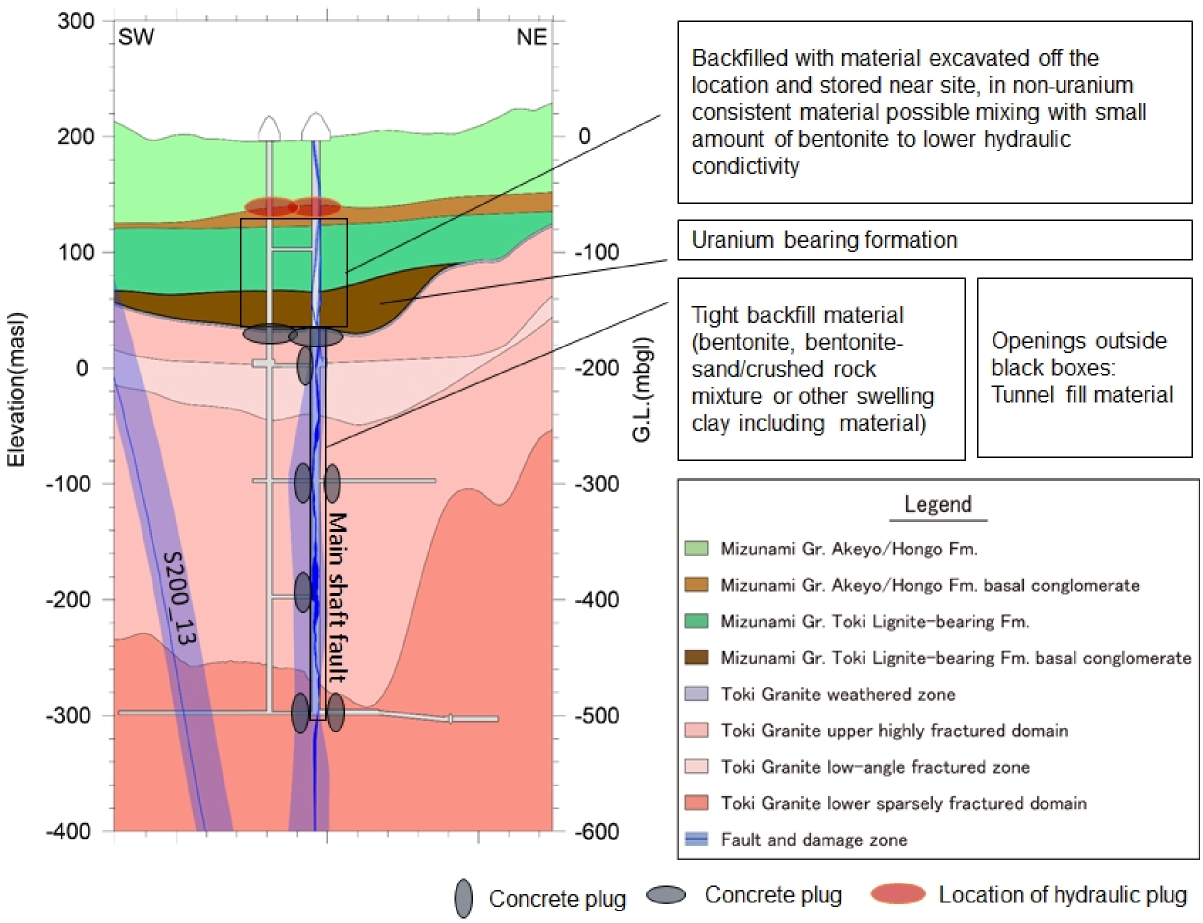


Figure A3. *Mizunami URL closure design alternative A.*

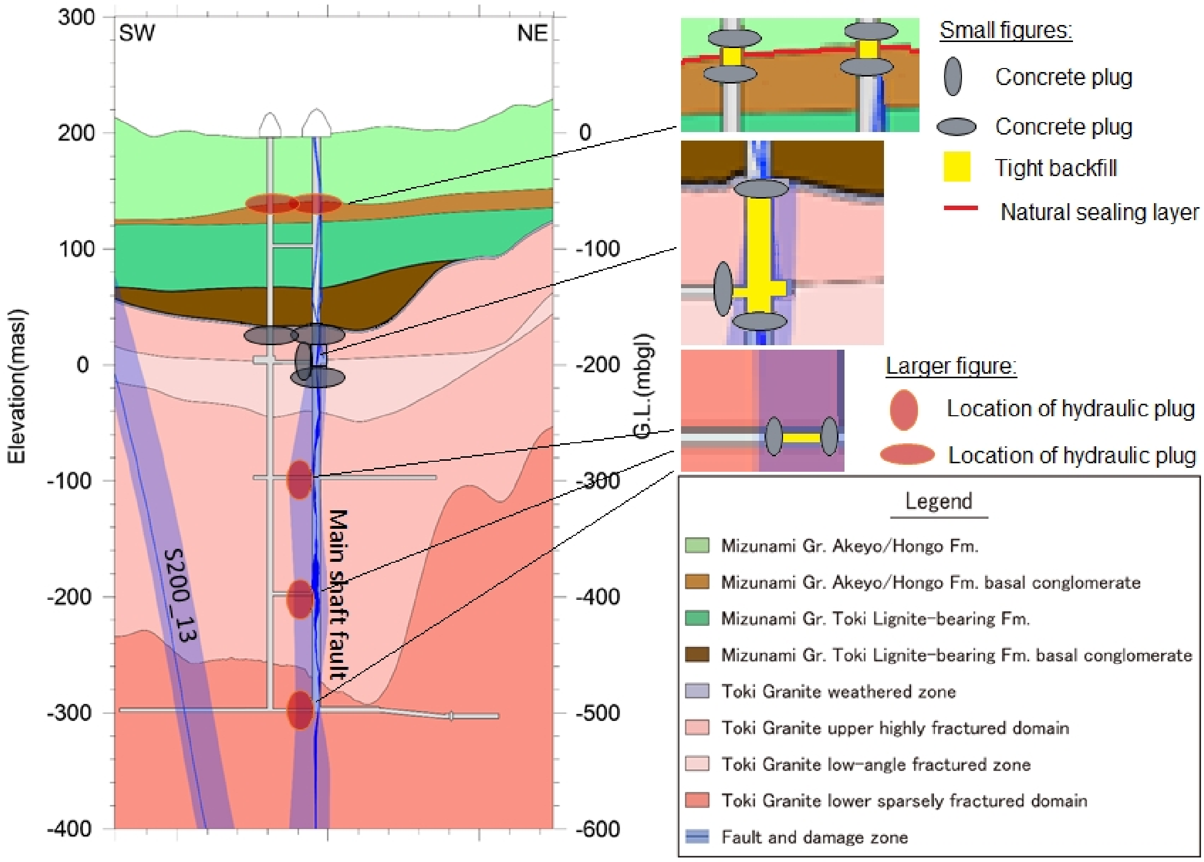


Figure A4. *Mizunami URL closure design alternative B.*

To fully utilise the unique possibility to design and plan this experimental closure procedure, the potential of international collaboration should be checked. The final closing project would benefit of such collaboration, since the same problems are of interest in many countries. MIU site also provides settings to perform closure related tests in both environments, sedimentary and crystalline.

Despite of the fact that the plan is yet to be reviewed by the international organisations, a preliminary research theme is presented, which includes first and foremost the site scale implementation of the closure and monitoring of its performance, especially focussing on the response of the site. This geoscientific research is targeted to especially hydrogeological response, but also hydrogeochemical aspects are included. Potential exists also for rock mechanical studies and seismic monitoring.

Smaller scale experiments would be advisable to be added in the closing project, since a lot of potential exist for various topics that are related to closing facilities. Some examples of these have been listed in this report, but the final list should be developed through the project group initialising the closing project.

The main constraints in the closure of the MIU are the time and the technical challenges. However, these are only briefly mentioned, since the main aim has been in presenting the optimal plan from scientific and environmental safety point of view, addressing also the safety of local people. Budget issues are not discussed in this report.

The full scale closing of the MIU would be advisable to be monitored also after the actual operational phase in order to get relevant results. This would be of interest of the local community, since in this way also general environmental follow up could be provided long enough.

The main output of the closing project would be increasing the information on the performance of the closure in geoscientific point of view. The experience on the technical procedures would be of great value also. These both are in line with the overall objectives set for the Mizunami URL. In addition the project can provide an excellent reference for both cost estimation and scheduling of work phases of potential geological repository closure.

1 INTRODUCTION

1.1 Background

Japan Atomic Energy Agency's (JAEA) role is to serve both implementers and regulators of the disposal of Japan's radioactive waste and spent nuclear fuel. A general timeline for geological disposal in Japan by Nuclear Waste Management Organization of Japan (NUMO) is given in Figure 1. Plans for general repository concepts and overview on NUMO's plans for geological disposal of transuranic (TRU) and high level waste (HLW) are briefly described at www.numo.or.jp.

Currently, JAEA is planning of closing the Mizunami Underground Research Laboratory (MIU/ Mizunami URL) within the next ten years. JAEA's interest is to plan and implement the project so that, in addition to the efficient closure of the MIU, relevant understanding, experience and data for the future repository development programs in Japan is produced.

In addition to serving the Japanese program of nuclear waste disposal, there is a great potential to attract interest also internationally, since large scale backfilling, closure and especially monitoring experiments are still somewhat rare.

A strategy for the closure of MIU is needed to be able to decide on the closure concept including the materials to be used, procedures for backfilling the tunnels and the shafts, the need for experimental work to support the concept and material selection and working procedures as well as to plan the monitoring of the closure performance (both targets and duration).

In this proposal for a strategy for MIU closure, a review on the closure development internationally with a focus on the Finnish case is presented in order to provide background for the strategy proposed for JAEA. This is because in Finland, there have recently been substantial efforts to develop closure design for a spent fuel repository. A proposal for MIU closure is made focussing on how to proceed with the project and to make the most of the great potential for development and gaining scientific knowledge from this URL site. The strategy takes into account the time constraints set for the closure.

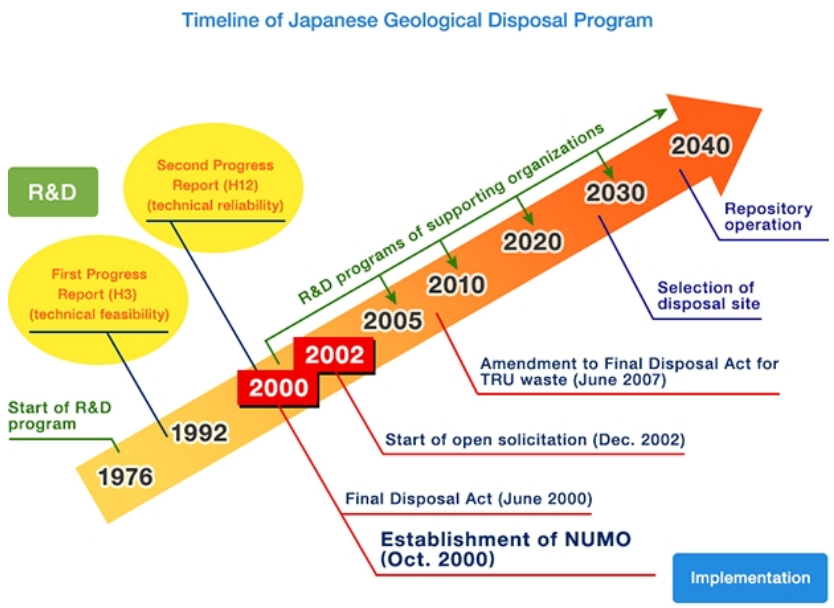


Figure 1. *A timeline of the Japanese geological disposal program (NUMO, http://www.numo.or.jp/en/jigyou/new_eng_tab01.html).*

1.2 Current status of MIU

MIU is located in Toki granite in Tono area (Figure 2). The URL project was initiated already in the 90's and is ongoing today.

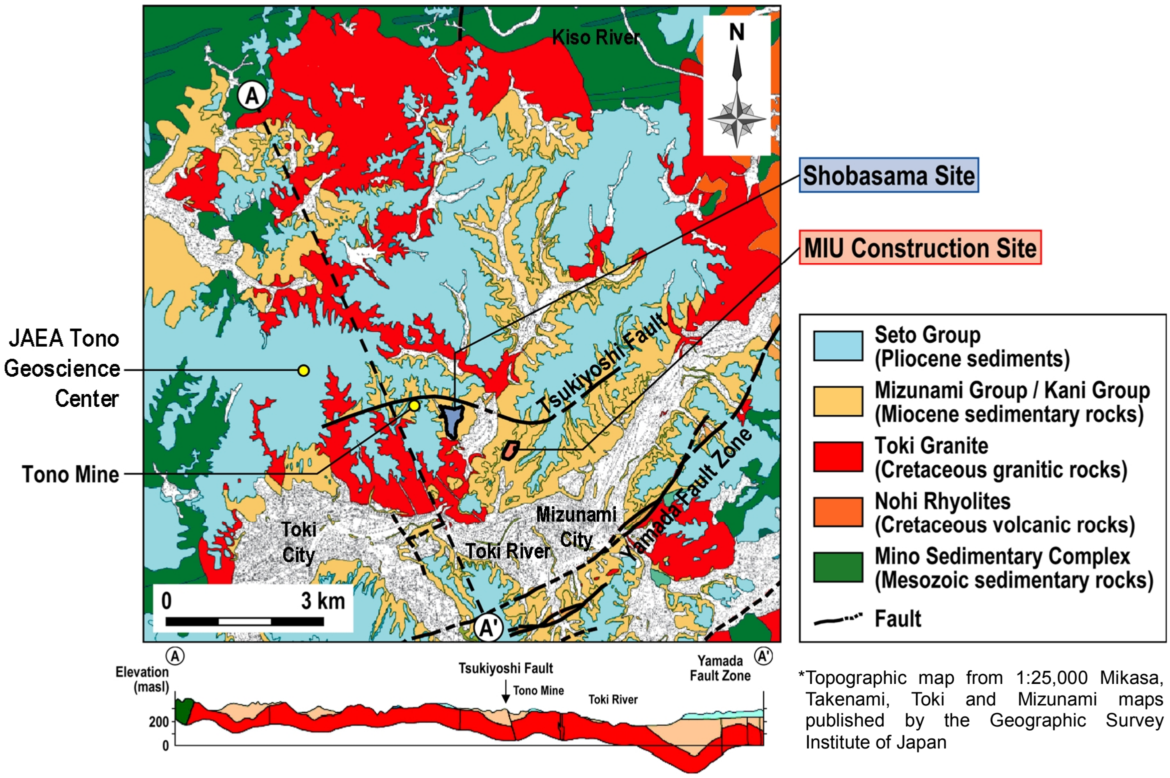


Figure 2. *Location and regional geology surrounding MIU (Saegusa & Matsuoka 2011, Simplified from Itoigawa 1980).*

The operation of MIU has been divided in three phases. Phase I focussed on the surface based investigations and the main achievements of this phase have been reported in Saegusa & Matsuoka (2011). During Phase II the project moved underground and the research galleries were excavated. Phase III is/will be focussing on various experimental and testing operations.

The overall project goals through the Phases I-III are:

1) to establish techniques for investigation, analysis and assessment of the deep geological environment, and
2) to develop a range of engineering for deep underground application (JAEA 2010).

MIU project was initiated in 1996 and Phase I was completed in 2005. Phase II started in 2001 and was conducted in parallel with Phase I for a few years. Phase II was completed at the end of 2009. The project is now at Phase III. The overall schedule for research and excavation is presented in Figure 3.

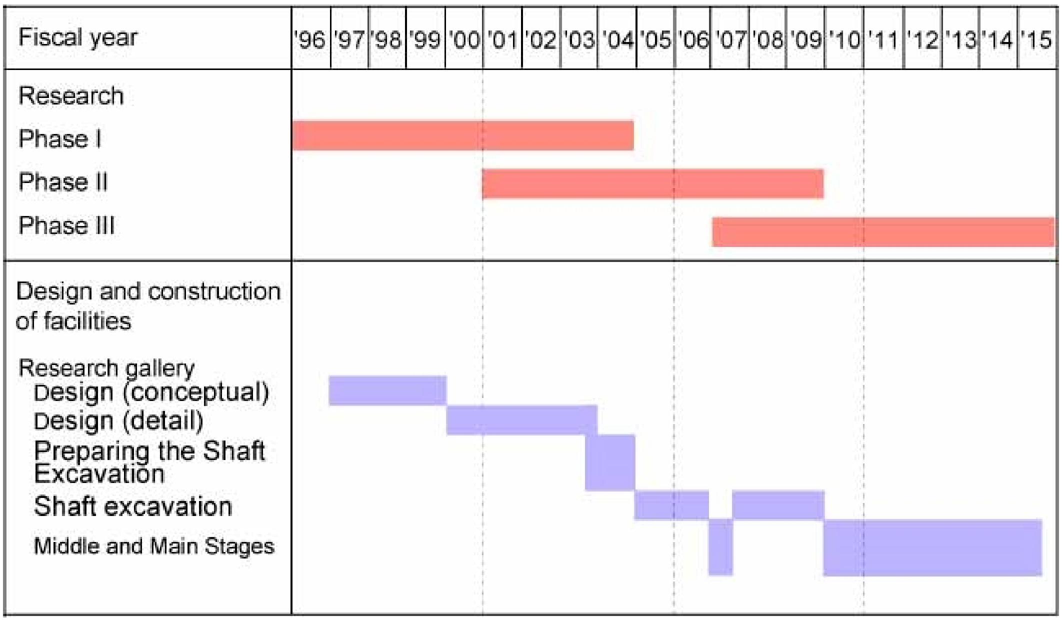


Figure 3. *The research schedule for the MIU project consists of three overlapping phases in a 20-year life shown as red bars. Blue bars show the design and construction phases (JAEA, http://www.jaea.go.jp/04/tono/miu_e/project/construction.html).*

The ongoing work has been conducted in a step-wise manner and it has produced continuously increasing amount of information regarding the site conditions and engineering of the underground spaces.

Specific goals were set for Phase I:

1) to construct models of the geological environment from all surface-based investigation results that describe the geological environment prior to excavation and predict excavation response,
2) to formulate detailed design concepts and a construction plan for the underground facilities, and
3) to establish detailed investigation plans for Phase II.

When continuing the project underground, goals were set for Phase II and as well as later on for Phase III. These are,

for Phase II:

1) to develop and revise models of geological environment using the investigation results obtained during excavation and determine and assess changes in the geological environment in response to the excavations,
2) to evaluate the effectiveness of engineering techniques used for construction, maintenance and management of underground facilities, and
3) to establish detailed investigation plans for Phase III,

and for Phase III:

1) to revise and improve the models of the geological environment using the results of underground investigations and determine any change in the geological environment in response to research gallery extension, and

2) to evaluate the effectiveness of engineering techniques used for deep underground excavation.

JAEA has listed the main factors for characterisation of the site and production of data for the needs of different disciplines: safety assessment, design & construction of underground facilities and environmental assessment. These factors and a list of data requirements are listed in Figure 4. Note that the division for different uses is very general and in practice the information of all factors is relevant for safety assessment.

The current decision is that R & D in URL is continued until 2019. Afterwards the facility will be closed by (January) 2022 and the site shall be returned to the local government. These milestones place the main schedule constraints for the strategy planning in this report.

Specific experiments have been planned to be conducted at -500 m level of the URL between 2015 - 2019 (ending March 2019). The research gallery at southern side is intensively fractured, while the northern side gallery is located in sparsely fractured rock.

In the southern side two experiments have been planned:

- Mass transport experiment (a tracer test using sorption tracer in advective conditions), and,
- Grouting experiment (including post-grouting test, monitoring of the leaching and investigation of grout durability and monitoring of the leakage through EDZ around plug)

For the northern side:

- Mass transport experiment (a tracer test using sorption tracer in diffusive conditions), and,
- Monitoring and characterisation of EDZ/EdZ, including monitoring practice development.

For the period of 2019 until closure a drift closure experiment with backfilling has been planned, including potentially installation of monitoring equipment, emplacement of backfill and plug, monitoring and retrieval test. However, these plans have been made before the knowledge of the final schedule given above. In this report these backfill plans are revised and recommendations given.

Figure 4. Important factors characterised and related data requirements (Saegusa & Matsuoka 2011).

1.3 Scope of the work

The scope of this work is mainly restricted to crystalline environments regarding the reviewed literature. The focus is on the 'closure' meaning the backfilling and sealing of the tunnels that provide the necessary routes and infrastructure to access and operate a deep geological disposal facility. Also borehole sealing is generally considered to be part of the closure. However, regarding closing MIU this is not the main focus in this report.

The main objectives of this report are:

- to review relevant literature regarding the development of the closure systems, related requirements and how they could be applied in MIU closing phase.
- to propose a strategy for MIU that is fitted to the site conditions for closing the URL. The strategy aims at the best possible outcome of the demonstration and monitoring potential for such an experimental site.

- to propose an overall strategy that can be brought forward and be planned in more detail in the next few years before closing of MIU is realised prior January 2022.

2 Description of underground openings and drill holes

Excavation of the underground spaces was initiated in 2003. Layout of the underground facilities is presented in Figure 5. The facility consists of two shafts, a ventilation shaft and a main shaft. Tunnels for the research purposes have been excavated on five different levels at 100 m interval. The deepest level is at -500 m (from ground surface). Excavated rock has been removed from the site and has been piled in a landfill and from Toki Lignite-bearing formation also to sheltered storage.

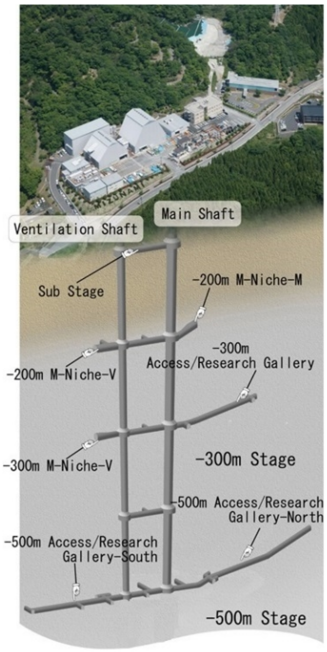


Figure 5. *Layout of the underground facilities at MIU (JAEA, http://www.jaea.go.jp/).*

The total volume of MIU is 48,766 m^3. Different parts of the facility are shown in Figure 6 and the volumes of the different parts are given in Table 1.

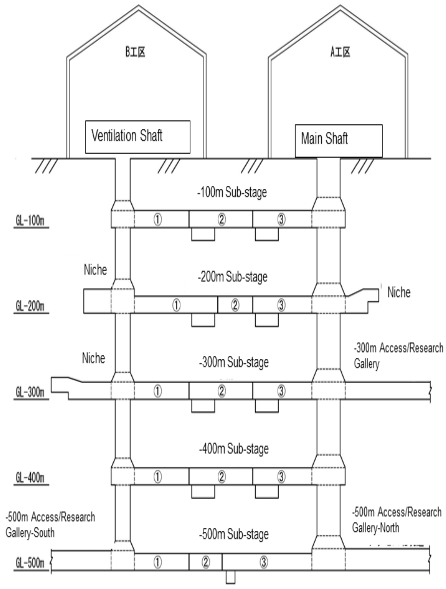


Figure 6. *Underground openings at MIU; see volumes in Table 1.*

Table 1. *Volumes of underground openings at MIU, see Figure 6 for geometry.*

		Ventilation Shaft		Main Shaft	
Depth*	**URL parts**	**Specification**	**Volume (m³)**	**Specification**	**Volume (m³)**
GL-0 ～100	Shaft		2607		4160
	Gallery	Sub-stage①	64.8	Sub-stage②	174
				Sub-stage③	128.4
GL-100 ～200	Shaft		2723		4160
	Gallery	Sub-stage①	124.8	Sub-stage②	133.2
		Niche	393.6	Sub-stage③	118.8
				Niche	343.2
GL-200 ～300	Shaft		2614		4160
	Gallery	Sub-stage①	91.2	Sub-stage②	235.2
		Niche	186	Sub-stage③	142.8
				-300m Access/Research Gallery	1380
GL-300 ～400	Shaft		2614		5586
	Gallery	Sub-stage①	67.2	Sub-stage②	235.2
				Sub-stage③	166.8
GL-400 ～500	Shaft		2719		5743
	Gallery	Sub-stage①	62.4	Sub-stage②	207.6
		-500m Access/Research Gallery-South	2550	Sub-stage③	404.4
				-500m Access/Research Gallery-North	4470
Total volumes			**16,817**		**31,949**

*Depths are from ground level (GL).

Borehole investigations and excavation of the underground spaces have been done in a step wise manner as illustrated in Figure 7. In addition to MIU site also close-by Shobasama site has been investigated in detail. Boreholes have been located to provide data at different scales around the URL site; these scales are presented in Figure 8 and are regional scale, local scale and site scale.

There are boreholes in the area to provide the baseline and monitoring data for different scales (Figure 7).

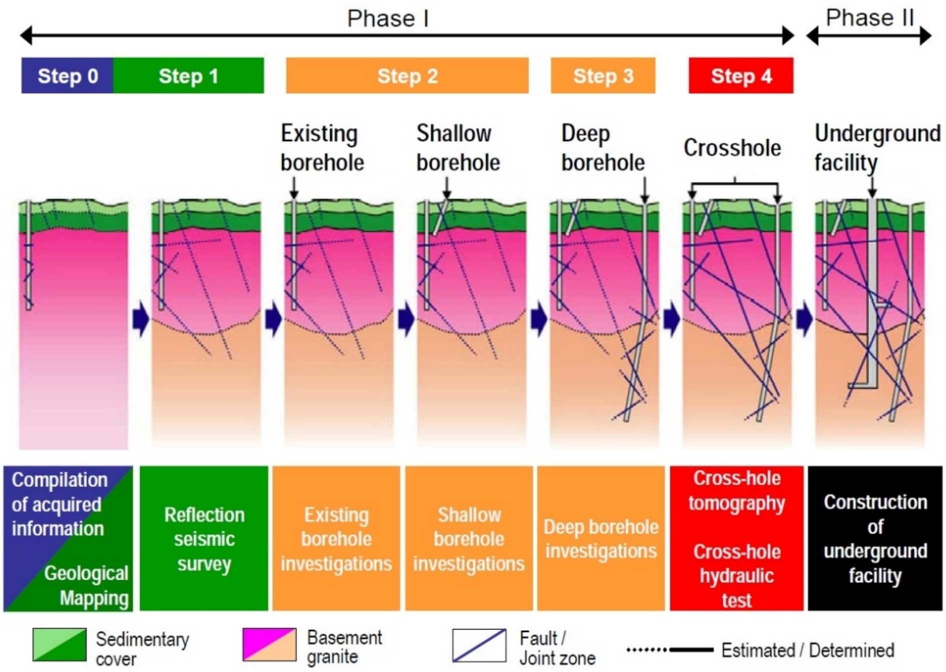


Figure 7. *Step-wise borehole and URL investigation phases during Phase I and II (Saegusa & Matsuoka 2011).*

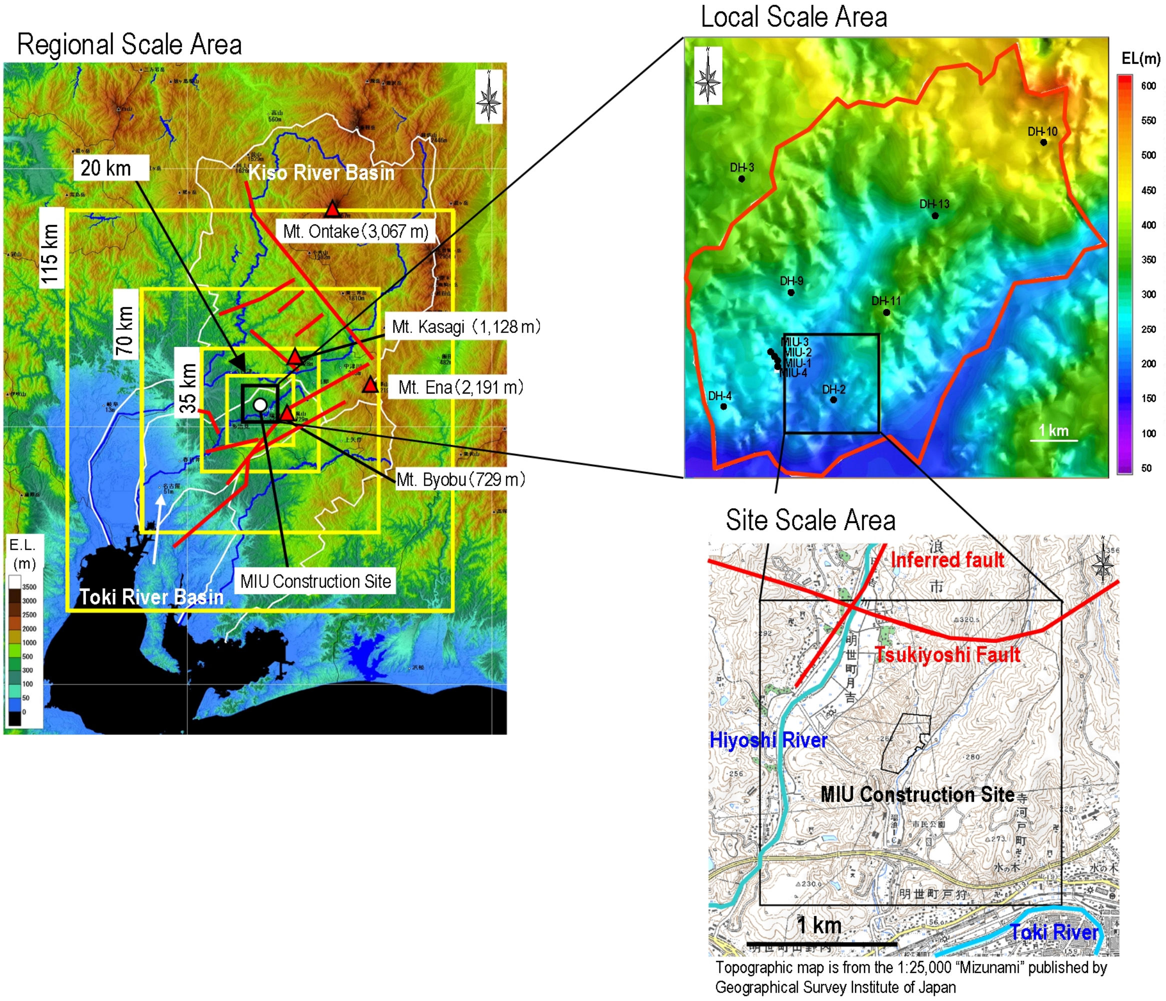


Figure 8. *Scales of investigation (Saegusa & Matsuoka 2011). In addition to these a block scale is used describing the volume around URL in detail.*

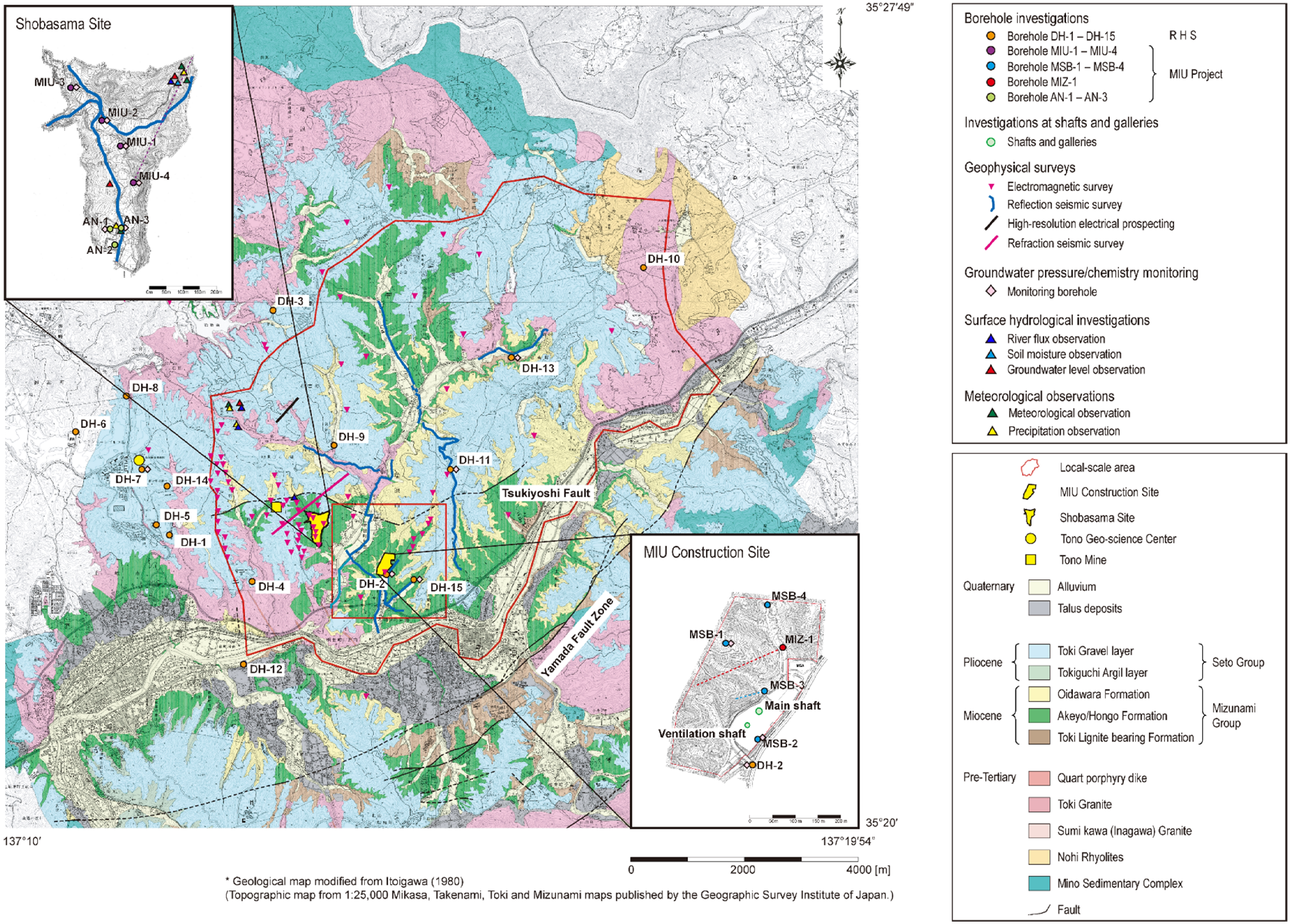


Figure 9. Overview of the borehole investigations around Mizunami area (Saegusa & Matsuoka 2011).

3 Description of the MIU site

3.1 Geological setting

As shown in Figure 2 the area, where MIU is located, is composed of granitic rocks (Toki granite, highly and sparsely fractured domains) with patchy sedimentary cover with varying thicknesses. The local scale geological model is shown in Figure 10. According to Saegusa & Matsuoka 2011, the Tertiary sedimentary rocks are lithologically divided into the Mizunami Group (age ca. 15-20 Ma) and the Seto Group (1.5-12 Ma), and:

- The Mizunami Group is further sub-divided into the Toki Lignite-bearing Formation (which contains some uranium), the Akeyo/Hongo Formation and the Oidawara Formation, in ascending order.
- The lower part of the Mizunami Group is mainly composed of tuff, silt/sandstone and conglomerate.
- The middle and upper parts of the Mizunami Group are mainly composed of mudstone and silt/sandstone alternating with shallow marine facies.
- The Seto Group consists of unconsolidated clay, sand and gravel.

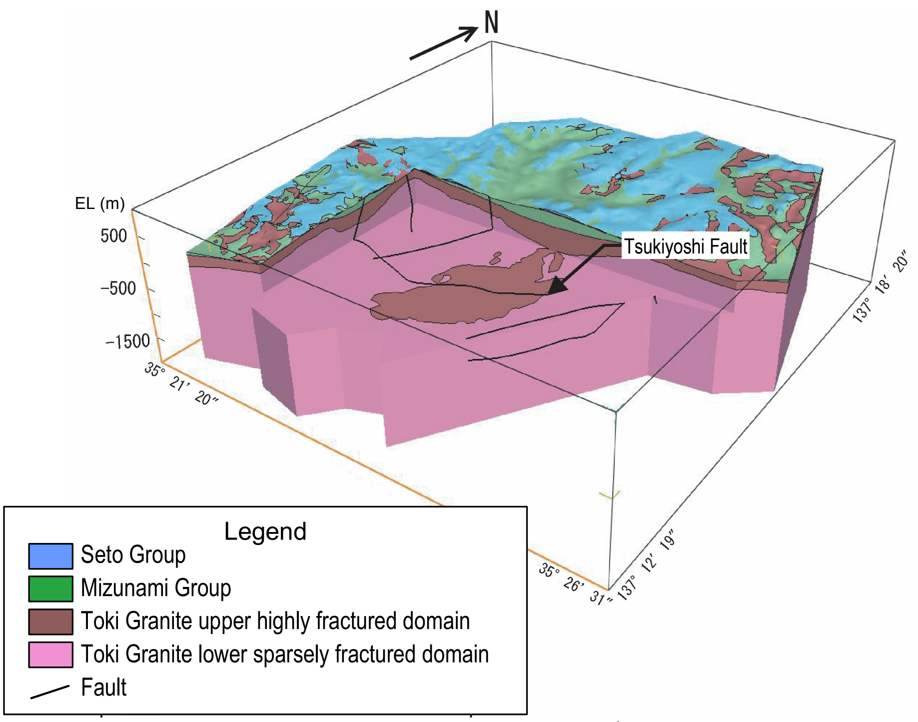


Figure 10. Geological model at local scale, Phase I (Saegusa & Matsuoka 2011).

In addition to horizontal sedimentary structures, local geology is characterised by faults. In Figure 11 and Figure 12, below vertical cross section and horizontal cross sections showing the main tunnel levels of MIU are presented. These figures illustrate the overall geology and the tunnels on site.

The faulting in the MIU area is dominated by sub-vertical structures, however also sub-horizontal fracturing and faults are present (e.g. Saegusa & Matsuoka 2011, Hayano et al. 2008, Tsuruta et al. 2009). Shafts at MIU are located in very different geological surroundings since the main shaft intersects a fault while the ventilation shaft is located in more intact rock volume, even though it is in highly fractured rock.

Seismic activity has also been monitored at MIU area. Monitoring results indicate that the magnitude of the vibration caused by an earthquake generally decreases with depth, which is consistent with existing knowledge (Niimi et al. 2012). Seismic monitoring on site has been enhanced since 2011 (Niimi et al. 2012).

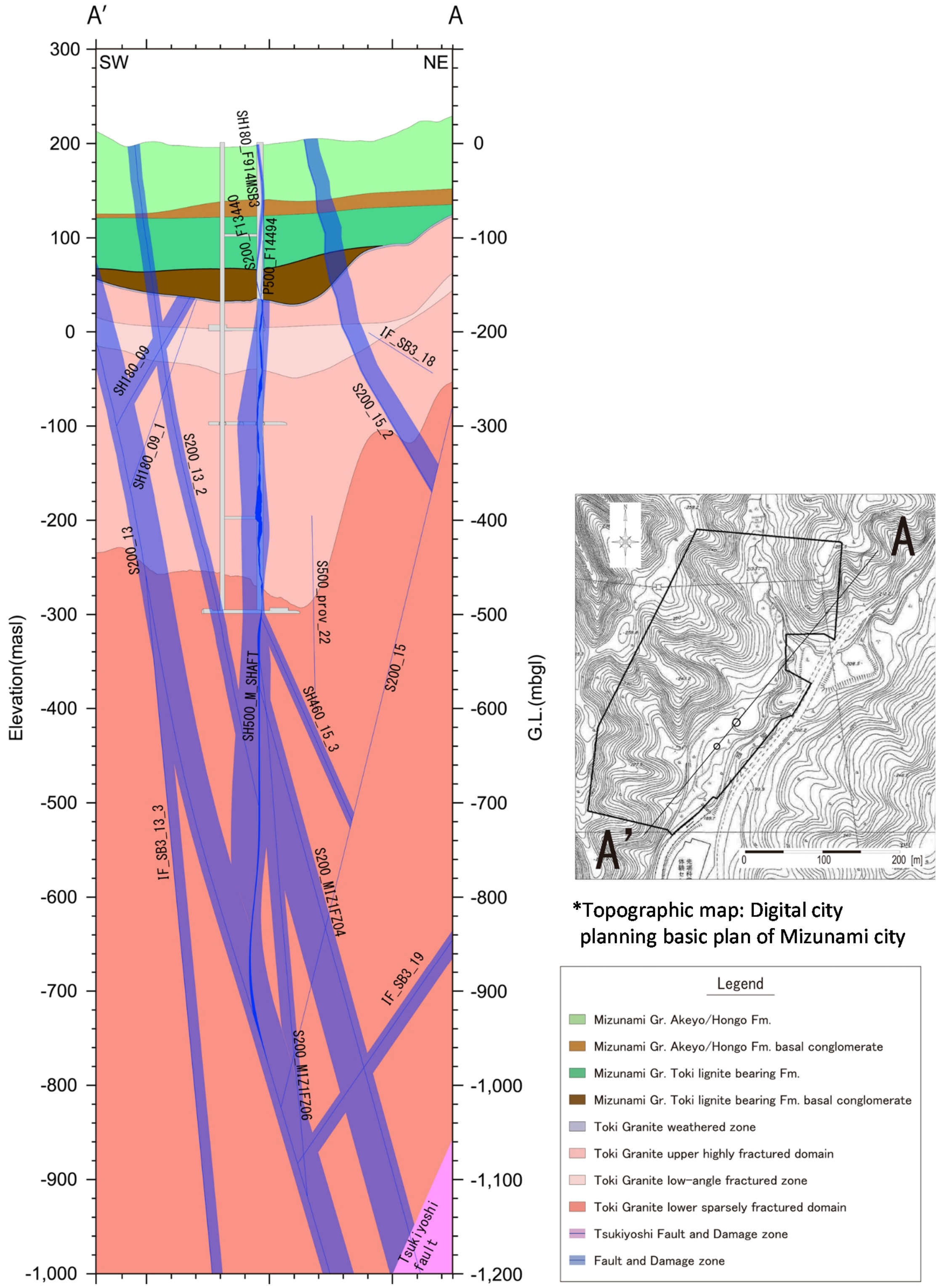


Figure 11. *Vertical cross section of MIU geological model showing two shafts and tunnels at different depths (100 m interval).*

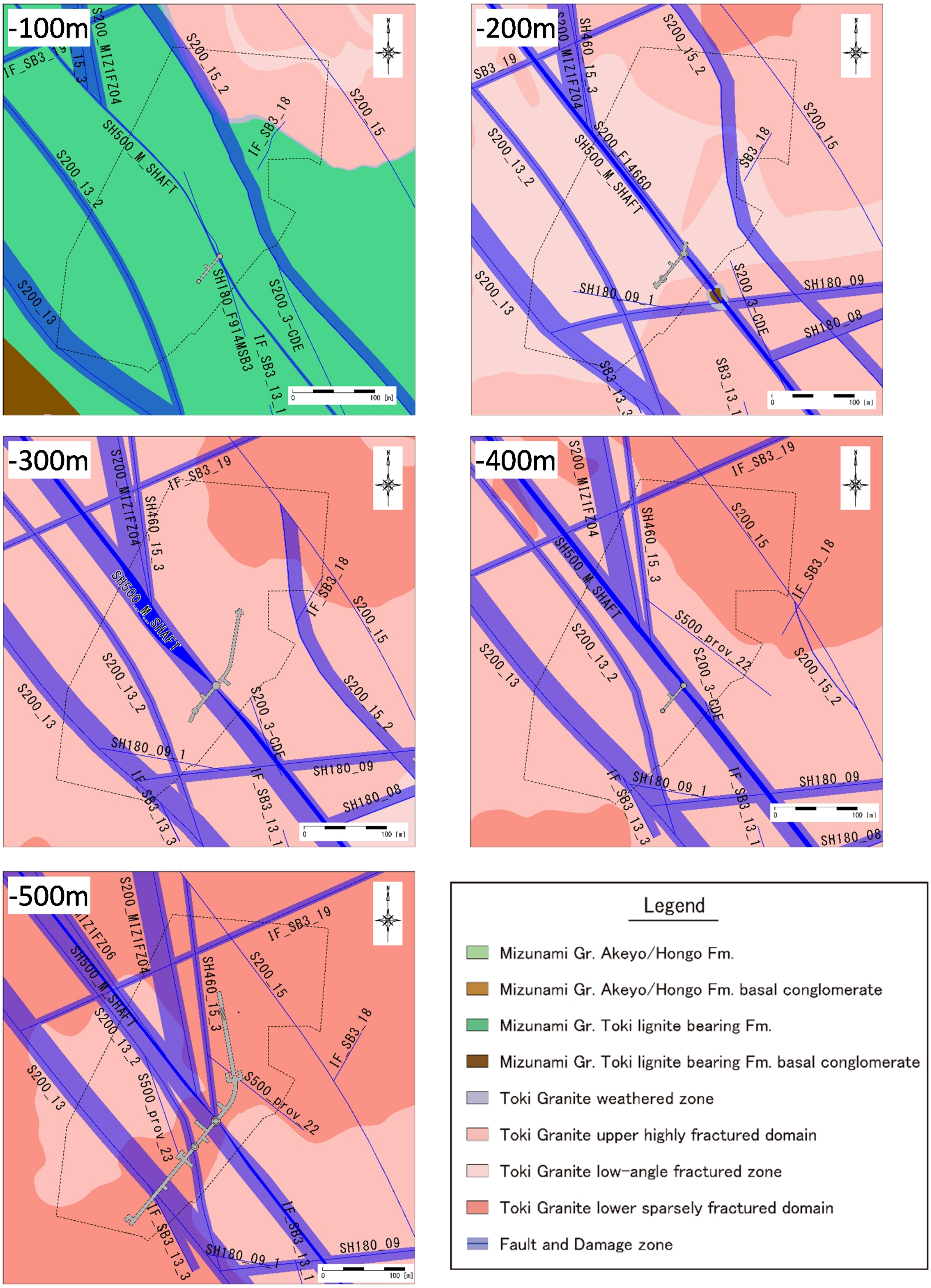


Figure 12. *Horizontal slices of the geological model.*

3.2 Groundwater system

During Phase I investigations a conceptual model of the groundwater flow system at MIU site was developed (Saegusa et al. 2009). An overall conceptual groundwater flow model based on surface based investigations is presented in Figure 13.

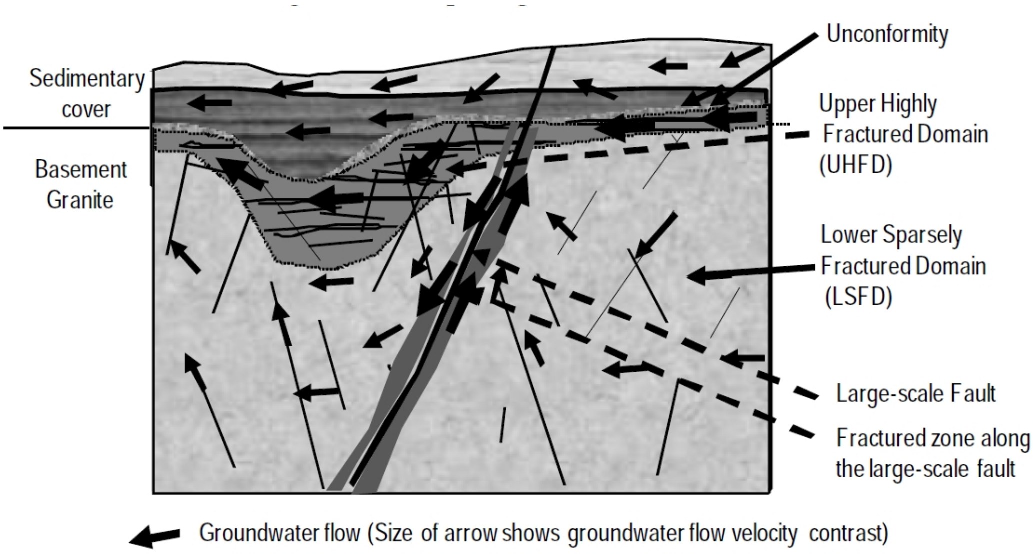


Figure 13. *Conceptual groundwater flow model (Saegusa et al. 2009).*

Although the granite in the MIU area is fractured, flow paths occur mainly along certain geological structures (e.g. Hayano et al. 2008). Hayano et al. (2008) observed that flow paths are observed both in low angle and high angle fractures. Especially in the case of ventilation shaft, the water conducting fractures seem to be predominantly the ones with no alteration. Fractures with alteration and resulting fault gouge contribute to water shut off. Hence, in the main shaft, there are very little inflows observed. An example of fracturing and their relationships with water conducting features is illustrated in Figure 14.

Hydrogeological characterisation of the MIU site has been done by using monitoring boreholes drilled in the area. Daimaru et al. (2010) have observed pressure changes during the excavation. MIU operation can be seen as a large scale pumping test that has had a large hydraulic impact on site. Before excavation hydraulic properties have been studied by a cross-hole hydraulic testing, but after excavation, more detailed description of hydraulic features at MIU site has been possible. Groundwater flow field is divided in domains by a fault that is intersected by the main shaft. This fault acts as a hydraulic barrier on the site.

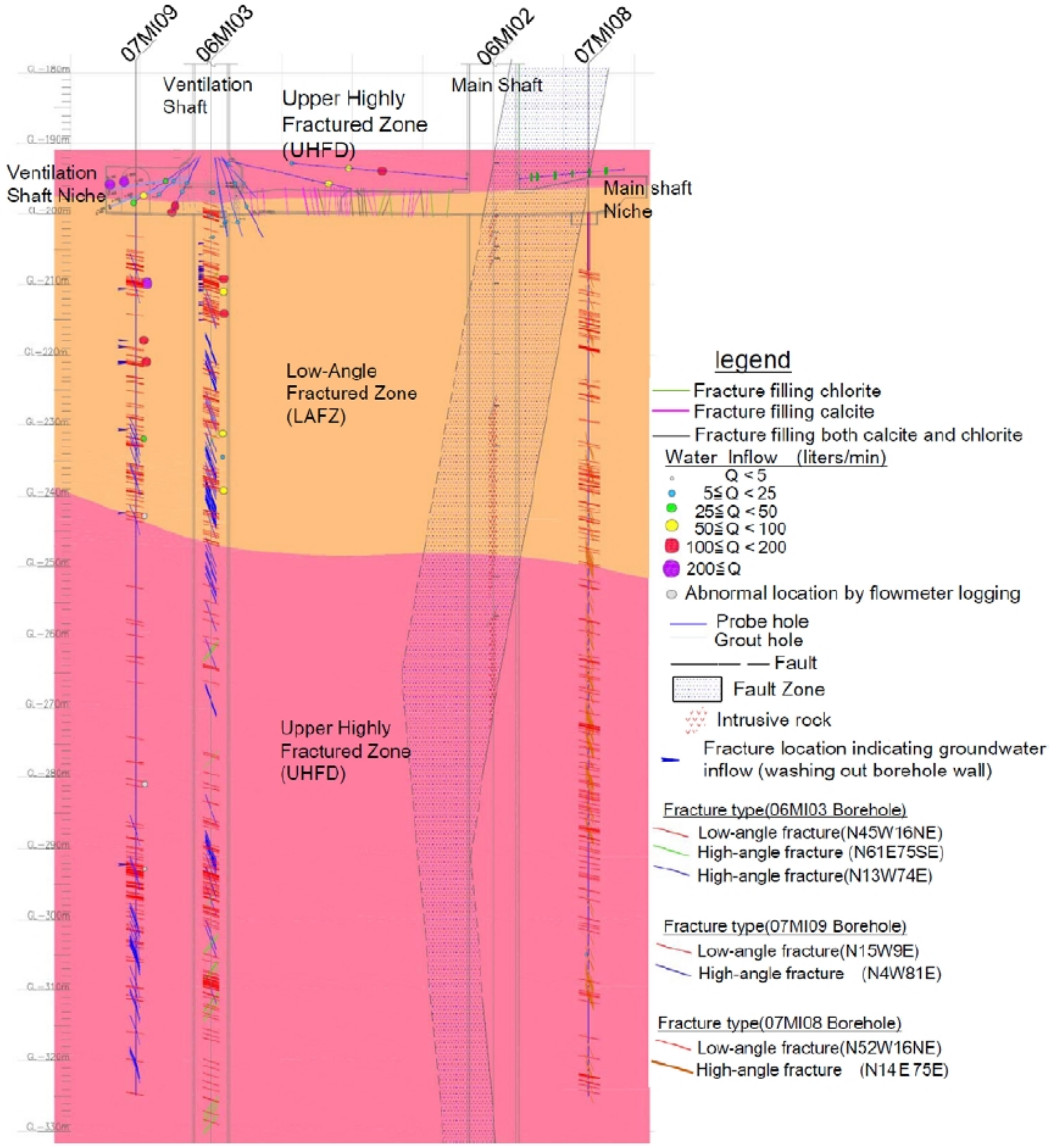


Figure 14. *Overview of the investigation results between -180m to -330m showing observed fractures and inflow locations in shafts (Hayano et al. 2008).*

Sedimentary cover forms a hydraulically distinct unit and it has been observed that the sedimentary formation (Toki lignite-bearing formation) above the basal conglomerate acts as a horizontal hydraulic barrier (Takeuchi et al. 2007). There are several less permeable units in Akeyo-Hongo, as well as in Toki lignite. One less permeable layer is located above the conglomerate as illustrated in Figure 15.

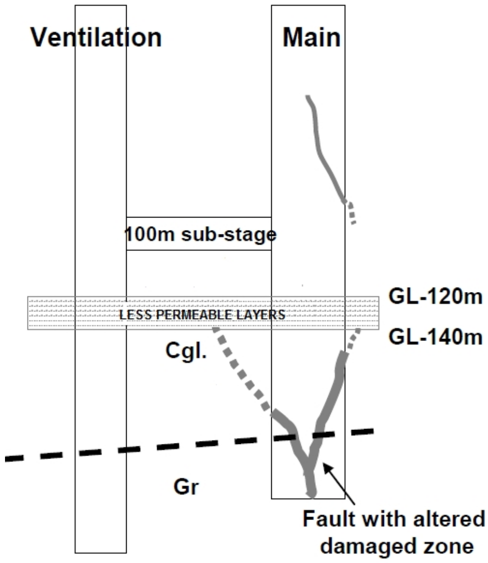


Figure 15. *Less permeable layer within Toki lingnite bearing formation (Modified from Takeuchi et al. 2007).*

An overview of the hydraulic conductivities of various geological domains at Mizunami is given in Table 2 below.

Hydrogeological modelling at MIU site has been conducted based on the available hydrogeological data. E.g. Ohyama et al. (2009) have compared the modelling and observed inflow results showing good agreement.

Table 2. *Hydraulic conductivities in various geological units at Mizunami (Saegusa & Matsuoka 2010).*

Hydraulic conductivity

Geological features and geological structure element			Log [k (m s^{-1})]
Sedimentary rock	Seto group		-5.0
	Mizunami group	Oidawara formation	-8.5
		Akeyo/Hongo formation	-7.6
		Akeyo/Hongo formation Basal conglomerate	-6.3
		Toki-lignite bearing foramation	-6.3
		Toki-lignite bearing foramation Basal conglomerate	-5.9
Toki granite		Upper Highly fractured domain	-6.7
		Low angle fractured zone	-5.4
		Lower sparsely fractured domain	-7.7

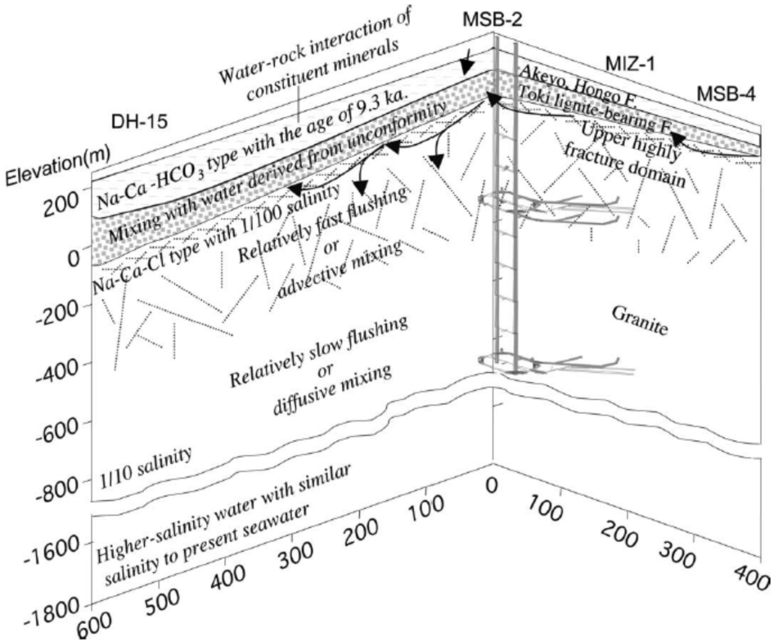
Seismic movements can also affect the inflow rates in underground spaces. This was observed in MIU during the 2011 Tohoku earthquake, which occurred off the Pacific coast of Japan. Groundwater pressure changes were observed around MIU in 15 boreholes (Niwa et al. 2012). In boreholes further than 1 km away from MIU a drawdown was observed. In contrast in boreholes within 500 m radius of MIU earthquake caused increase in heads. At MIU, soon after the Tohoku earthquake inflow volume of groundwater increased more than 10%, this anomalous increase of inflow volume of groundwater in the shafts is explained by the temporal recovery of the ongoing drawdown due to shaft excavation and by the earthquake-induced permeability enhancement in the main-shaft fault closely related to the heterogeneity of hydrogeological structure (Niwa et al. 2012). These observations show that the responses seen are related to tectonic setting and spatially variable contraction/dilation.

3.3 Groundwater chemistry

3.3.1 Baseline conditions

Hydrochemical baseline conditions for MIU groundwater system have been determined during the Phase I based on the data obtained from the surface-based investigations at Mizunami site by Iwatsuki et al. (2005). According to them, groundwater types present can be classified in two main types. Na-Ca-HCO_3 type groundwater is found in the uppermost sedimentary formations, Akeyo and Hongo. Within the deeper sedimentary sequence, Toki lignite-bearing formation and the basement granite, groundwater composition is Na-(Ca)-Cl type. There is a clear hydrogeological boundary between Na-Ca-HCO_3 type and Na-(Ca)-Cl type groundwater systems. Baseline samples have been taken from 5 drillholes in the MIU area. Salinity in the area is relatively low, although the deeper groundwaters within granite are gradually changing towards more saline conditions with increasing depth (Na-Ca-Cl type). In Figure 16 the hydrogeochemical conceptual model of the MIU site and TDS variation as a function of depth are presented. Details on the variation of the various groundwater samples vs. depth are given in Figure 17.

A



B

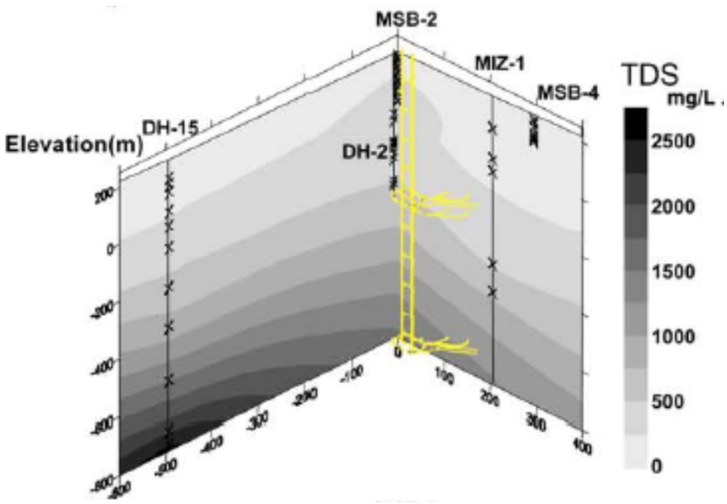


Figure 16. *a) Hydrogeochemical conceptual model in and around the MIU construction site. The arrows depict flow direction – length proportional to flow rate. The salinity of the Na–(Ca)–Cl type of groundwater in granite is probably controlled by ongoing flushing of fossil seawater, or mixing processes with paleo-hydrothermal water or fossil seawater that had already been flushed in the deeper part. The processes depend on hydrogeological conditions such as the groundwater flow rate and fracture frequency of granite. Groundwater is moving relatively slowly in the deeper part of the granite. b) TDS as a function of depth at MIU site (Iwatsuki et al. 2005). Note that the layout of underground openings in these figures is deeper than actually excavated, see Figure 5.*

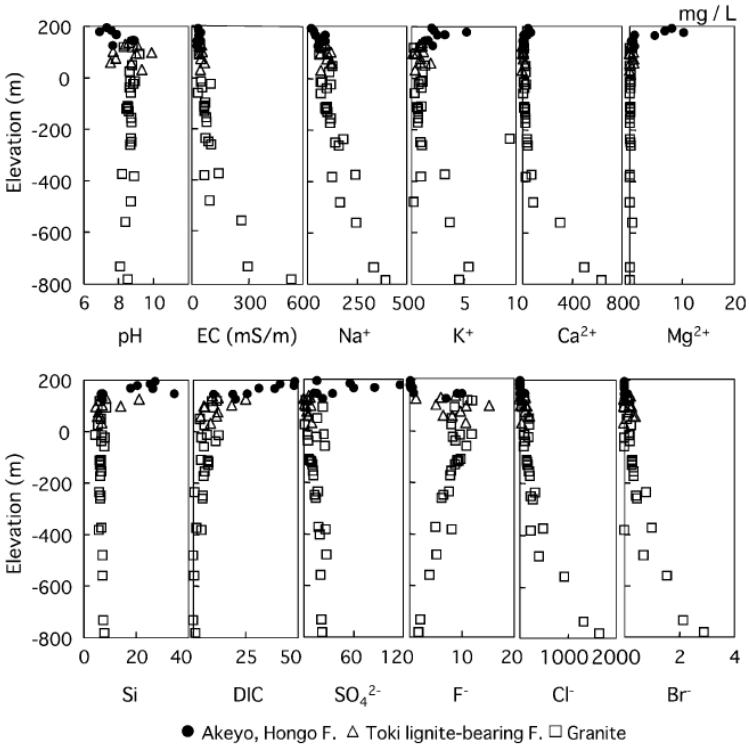


Figure 17. Groundwater chemistry in and around the MIU construction site. Both analytical errors and errors due to correction of drilling fluid contamination are smaller than the symbols used. The chemical type of groundwater can be divided into a Na–Ca–HCO3 type in the Akeyo, Hongo F. and a Na–Cl type in the Toki lignite-bearing F. and granite. The latter type of groundwater is subdivided into a Na–Cl type in the Toki lignite-bearing F. and shallow granite and a Na–Ca–Cl dominate type in deep granite.

3.3.2 Long-term evolution of the groundwater system

Hydrogeochemical and hydrological evolution of the MIU site has been evaluated by Mizuno et al. (2010) based on fracture calcite crystallisation events. Mizuno et al. (2010) have proposed a conceptual model of the evolution of the groundwater system at Mizunami area (Figure 18). Initial hydrothermal circulation after emplacement of the granitic body has been followed by meteoric water recharge after which the groundwater evolution has been determined by the sea level changes in the area due to transgression/regression and erosion. Current topographic evolution is controlled by uplift and meteoric recharge is an ongoing process. The major fault in the area, Tsukiyoshi, also may have affected the groundwater chemistry, esp. in relation to heterogeneous distribution of the older saline groundwater. Hydrothermal fluid is the oldest component of the groundwater system (75 Ma).

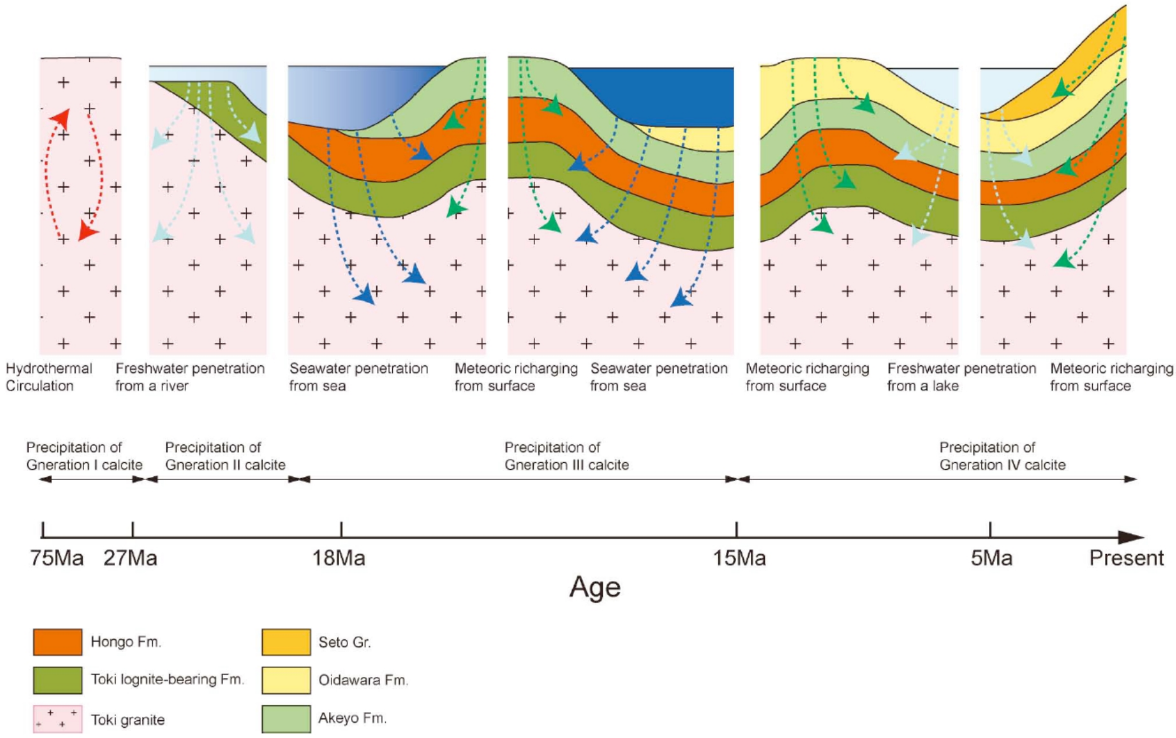


Figure 18. *Schematic diagram of the groundwater system evolution at the Mizunami area according to Mizuno et al. (2010).*

3.4 Stress state and Mechanical properties of rock

Geomechanical model was updated by Saegusa & Matsuoka (2010). The stress state, physical and mechanical properties of the rock types, as well as fracture distributions are shown in Figure *19*. Stress decoupling observed at the nearby Shobasama site is also observed at the MIU site. Two zones at MIU are identified (Sato et al. 2013):

- An upper zone (200 to 600 mabh); reverse faulting type, and,
- A lower zone (600 to 1,000 mabh); normal/strike-slip faulting type.

Directions of maximum horizontal stress are almost N-S to NW-SE. However, the data at 168 mabh and 638 mabh indicate the direction is ENE (Sato et al. 2013).

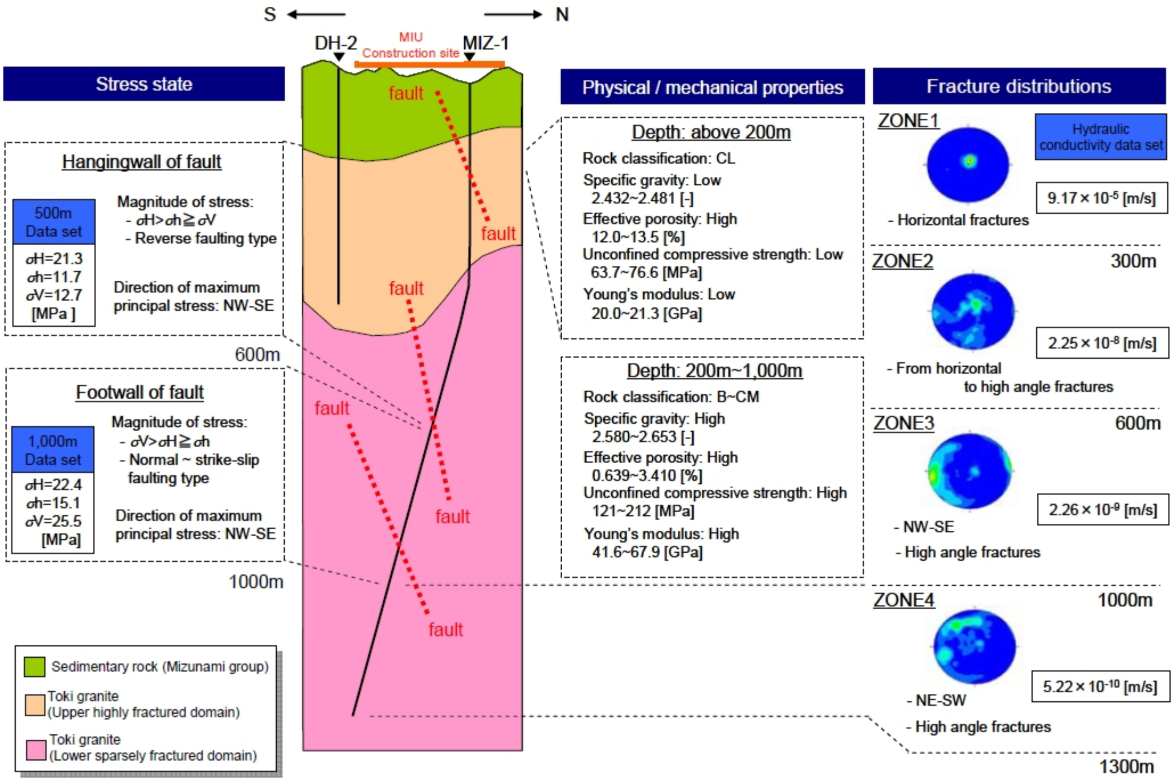


Figure 19. Geomechanical model of MIU (Saegusa & Matsuoka 2010).

3.5 Effects of excavation and operation

MIU site has been monitored continuously during excavation and operation for about 10 years. Monitoring results and numerical analyses indicate that hydrochemical changes are observed at least in 100 m radius from shafts in the groundwater system (in granite). These results have been reported in a paper by Iwatsuki et al. (2015). Both, upconing of more saline deeper groundwater and infiltration of low-salinity shallow groundwater, are observed. It is noteworthy that salinity changes observed around the facility are strongly controlled by fault structures. Especially at different sides of the "Main shaft fault" (M SHAFT in Figure 11), the results differ from each other. Inflows at the facility have been large during excavation, in the order of several hundreds of m^3/day. Excavation has caused large changes in the groundwater system. E.g. drawdown of groundwater table is seen over several hundreds of meters away from the shafts. It is anticipated that the groundwater composition will compare to that of shallow groundwater in the future (Iwatsuki et al. 2015).

Cementitious materials have been used throughout the facility at MIU. Shotcreting has been used in the tunnels extensively. Shafts have been excavated using blasting and mucking, two 1.3 m intervals per round, followed by concrete lining in every section (Shimono et al. 2004). Also pre-grouting was conducted at sections where water conducting fractures have been encountered at depths 191-251 m, 421-428 m, 446-453 m in ventilation shaft and at 300 m in access/research gallery. It is also worth noting that when shafts had been excavated down to 180 m shafts were flooded with highest level of water at about -50 m below ground level. Water collection rings have been installed to shafts with 25 m interval.

Inflows in the MIU facilities have been monitored since 2005. Changes in the inflow volumes since April 2012 to March 2014 are seen in Figure 20. The largest inflows occur between -200 m and -300 m depth.

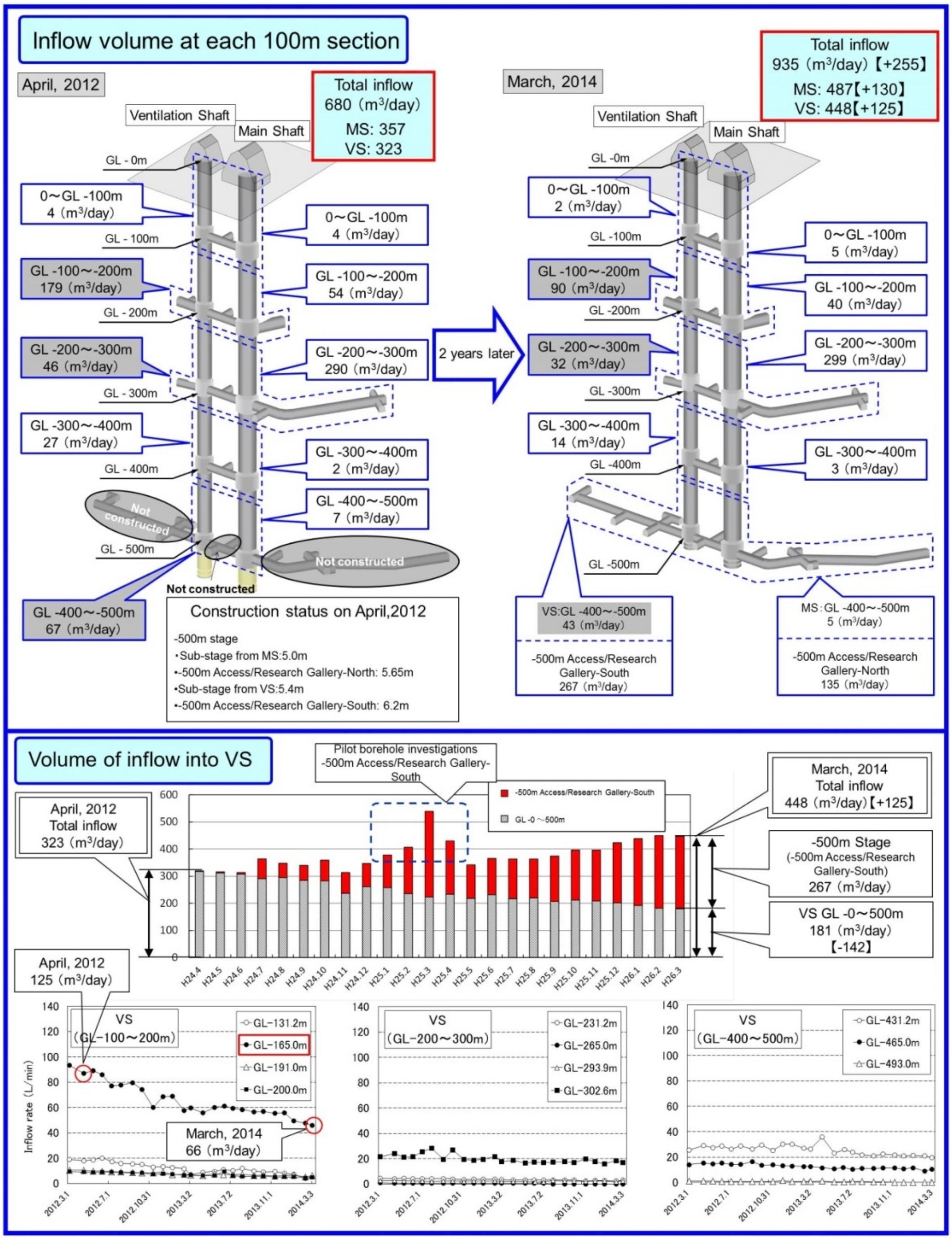


Figure 20. Spatial distribution of inflows into MIU facility. Years 2012 and 2014 (JAEA). VS= ventilation shaft, MS= main shaft, GL= depth from ground level.

3.6 Feedback for MIU closure

In relation to closing systems and demonstrations geological structures and hydraulic conductive features place demands for the design of the closure systems (cf. Sievänen et al. 2013). How details of site properties should be taken into account depends on the goals set in the strategy for closure. These options are discussed in Chapter 5.

At MIU the main geological features that need to be taken into account in the planning of the strategy for closing URL are especially:

- Horizontal layering in the geology (sedimentary vs. crystalline),
- Fracture intensity and related inflow,
- Fault structures and other fracturing, hydraulic relationships,
- Groundwater geochemistry (boundary conditions),
- Seismic activity, rock mechanics.

These general conditions, both natural and disturbed by the excavation, constrain what can be achieved in the closing project experimentally. High inflow may, for example, prevent some demonstration potential due to difficult operational conditions. Restoration of site after extensive pumping will need to be monitored.

On the other hand the site and its properties vary in different parts of the tunnels, offering great potential for comparative studies. In addition having both granitic and sedimentary rock types, construction of closure structures (e.g. shaft plugs) in these two different environments could be tested.

In addition to geological features also the amounts of cementitious and other construction materials affect the site, especially considering mid-term monitoring. One constraint for the strategy development is that the existing shotcreting cannot be completely removed from the galleries prior to the closure.

Site properties also affect the engineering and actual implementation of some underground structures and backfilling. The international projects discussed in Chapter 4 give a good basis for selecting the closure concept and materials to be used, however, the MIU closure project provides an opportunity to obtain information on some potentially new materials (e.g. shot clay, see e.g. Alessio et al. 2014 and Chegbeleh et al. 2014) and to develop the existing solutions.

4 Review of projects for closing tunnels and monitoring restoration

4.1 Constraints of closing tunnels

4.1.1 General requirements

Closing of the underground excavations is the final step in the geological disposal operation. Depending on the concept employed there may be various types of backfilling and sealing components in the system and their requirements may differ in relation to the safety functions assigned to them. For example backfilling close to the waste containers may have more stringent requirements than the sealing systems further away. In this work, the scope is defined to discuss mainly tunnel backfilling and plugging.

In general, closing the facilities include thus more variable conditions than expected for the waste container near field. Safety functions are defined specifically to each project, but the overall aim is to restore the conditions in the host rock in a way that the site properties remain suitable for the long-term safety of the repository. According to IAEA (2011a):

"A disposal facility shall be closed in a way that provides for those safety functions that have been shown by the safety case to be important after closure. Plans for closure, including the transition from active management of the facility, shall be well defined and practicable, so that closure can be carried out safely at an appropriate time."

Further, it is defined that:

"Closure of a geological disposal facility involves activities such as backfilling and sealing of the underground openings of the disposal facility. The purpose of closure is to try to restore, as far as practicable, the initial natural conditions of the host rock before any excavation is started (IAEA 2011a)."

In this work, the scope is defined to discuss mainly tunnel backfilling and plugging. It is of most importance that closure is included in the safety case from the beginning, as defined also by IAEA (2011a):

"Post-closure performance of a geological disposal facility should be considered in the initial design and in subsequent updates to the safety case. Prior to regulatory approval for facility closure, the safety case should be updated to provide sufficient evidence that the closure system will be effective and that the safety of the geological disposal facility after closure will be in accordance with regulatory requirements. The effectiveness of the closure system could be shown by demonstrating an understanding of the natural evolution of the site, by in situ testing, by data analysis and modelling and by the use of suitable natural analogues."

Closing MIU would greatly increase the information of the potential closure components and act as a possible demonstration on the ability to implement these structures according to requirements. Such a demonstration would be of interest for the development of the geological disposal in Japan as well as valuable also for other organisations responsible for geological disposal of radioactive waste worldwide.

Natural analogues have not been used in their full extent for demonstrating the safety of the closure systems. In this field there is a lot of potential for further research. This is mainly due to the fact that design has been at general level, and likely to go through some changes in many organisations. However, the material selection is fed by the information gained from natural materials used also in the near-field barriers (clays, cement etc.).

The case specific nature of the requirements for closure is further emphasised by IAEA (2011a):

"The disposal facility has to be closed in accordance with the conditions set for closure by the regulatory body in the facility's authorization, with particular consideration given to any changes in responsibility that may occur at this stage. Consistent with this, the installation of closure features may be performed in parallel with waste emplacement operations. Backfilling and placement of seals or caps may be delayed for a period after the completion of waste emplacement, for example, to allow for monitoring to assess aspects relating to safety after closure or for reasons relating to public acceptability. If such features are not to be put in place for a period of time after the completion of waste emplacement, then the implications for safety during operation and after closure have to be considered in the safety case (IAEA 2011b)."

Closure demonstration and monitoring of Mizunami URL would produce relevant information for both the implementers and regulator regarding the way closure is accounted for in the safety case during its multiple iterations during the siting and licencing process for the actual repository in the future.

Finally, a remark is given also regarding environmental remediation and decommissioning of the surface facilities (IAEA 2011a):

"Closure of a geological disposal facility should also include decommissioning of surface

facilities and undertaking any environmental restoration necessary, and may include the construction of durable markers."

4.1.2 Safety functions in deep geological disposal projects

Most volumes of MIU are located in a crystalline environment. It is worth noting that in sedimentary sites, the requirements for closure may differ from those of crystalline sites. However, within the crystalline environments, the closing solutions are multiple, and depend greatly on the overall design, the properties of the surrounding rock and the requirements placed upon the closure. In case of crystalline environment, the fracture system forms the preferential pathway between the surface and the repository depth, and thus the requirements set for closure aim to make sure that significant new pathways are not created.

Safety functions of the closure established by two organisations internationally have been listed in Table 3.

Table 3. *Safety functions related to closing facilities – examples.*

Organisation and reference	Safety functions
Posiva Oy Finland (Posiva 2012b)	*Closure shall prevent the underground openings from compromising the long-term isolation of the repository from the surface environment and normal habitats for humans, plants and animals.*
	Closure shall contribute to favourable and predictable geochemical and hydrogeological conditions for the other engineered barriers by preventing the formation of significant water conductive flow paths through the openings.
	Closure shall limit and retard inflow to and release of harmful substances from the repository.
SKB Sweden (SKB 2010a)	*Closure shall prevent that water conductive channels, that may jeopardise the barrier functions of the rock, are formed between the repository and the surface.*
	Closure shall not significantly impair the barrier functions of other barriers.
	The closure in main tunnels shall prevent that the backfill in deposition tunnels swells/expands or is transported out from the deposition tunnels.
	The closure shall keep the closure in underlying or adjacent underground openings in place.
	The closure in the upper part of the ramp, shafts and boreholes shall significantly obstruct unintentional intrusion into the repository.
	Closure shall be long-term durable and maintain its barrier functions in the environment expected in the final repository.

4.2 Review of selected closing projects

In this chapter, different projects related to closing of the facility are reviewed in order to provide scientific basis for discussion on the MIU closing strategy. These projects are briefly presented in the following Sections.

The majority of the URL experiments are component specific performance tests, or are designed to address specific long-term safety related processes. Some large scale repository EBS tests have been done. There are practically no site scale closing experiments done in the field of radioactive waste disposal that would include closure of an entire underground facility and monitoring of the site.

However, there is a vast amount of tests that include various types of monitoring systems at different scales. The details of tests of various materials, and their performance, are beyond the scope of this report. Here, the aim is to list some relevant information available for developing strategy for closing MIU.

4.2.1 Spent nuclear fuel repository at Olkiluoto, Finland (including ONKALO Underground Rock Characterisation Facility)

In Finland, Posiva Oy has applied for the construction licence for a geological repository to be built in a crystalline rock at Olkiluoto site in south-western Finland. The current design for the repository (Figure 21) includes a generic design for the closure of the facility. It has been designed taking into account the site specific conditions and their future evolution (see below) and thus utilises different materials at different levels and parts of the tunnels and shafts.

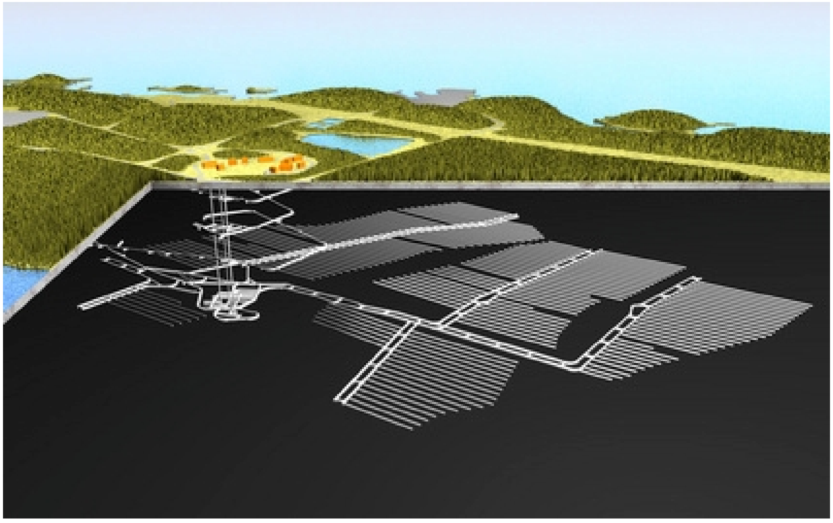


Figure 21. *Shematic figure of the disposal facility at Olkiluoto Island, Finland (Figure: Posiva Oy).*

During design development for closing spent fuel repository at Olkiluoto, Dixon et al. (2012) reviewed a vast amount of literature available for backfilling and plugging in crystalline rock environments. In addition to discussing the results from the laboratory and small scale tests, also the available information on the larger scale demonstrations were reviewed. Special attention were given to large scale field tests done at Stripa mine, Sweden (plugging test; Gray 1993), at Äspö URL, Sweden (backfilling and plugging tests; see e.g. Gunnarsson et al. 2003, Gunnarsson & Börgesson 2003 and SKB 2009) and Canadian URL tests (tunnel sealing projects; Chandler et al. 2002, Martino et al. 2008) and enhanced sealing projects (see e.g. Dixon et al. 2009).

As concluding remarks in relation to overall closure planning Dixon et al. (2012) state regarding plugs:

"The use of plugs within the disposal facility is important to both the short- and long-term performance of the closure system. These are primarily expected to consist of cement-based materials (concrete) and have hydraulic or mechanical functions that are associated with their location and the site-specific conditions. Selection of the location for each of the plugs will be vital in assuring their performance."

and regarding backfilling:

"Information currently available indicates that backfill materials can be installed to sufficient density using either in situ compaction or as an assembly of precompacted swelling-clay blocks and then pellets placed between the blocks and the surrounding rock. The swelling and

hydraulic behaviour of a range of potential backfill materials has been summarised and provides a means of tailoring fill materials to the surrounding conditions. For regions requiring stringent material performance, backfill of adequate characteristics can be identified and specified. For regions requiring less stringent performance (e.g. low hydraulic conductivity, high strength)*, appropriate materials can also be selected based on such information. The effects of groundwater conditions and rate of inflow to the excavations have been identified as potential issues with regards to system robustness and means to address them discussed."*

To full fill the safety functions (see Table 3), the closure is designed in a way that flow paths via tunnels would not form (i.e. better ones than the existing flow routes in the bedrock). The material selection is done according to material parameters and taking into account its expected behaviour in designed location. Hydraulic plugs are used to verify isolations and to isolate hydraulic zones. Materials are compatible with other EBS components and do not jeopardise functions of other components. Closure materials are not specifically designed to be radionuclide retarding, but with limited flow, the transfer of potentially released radionuclides would be limited significantly.

The overall design of the closure structures is presented in Figure 22 and described in detail by Sievänen et al. (2012).

The design takes into account the Olkiluoto bedrock data and especially the groundwater data. The main parameters taken into considerations are the transmissivity of fractures, hydraulic conductivity of bedrock sections, mechanical strength, fracture zones, and groundwater chemistry. The weak and hydraulically conductive sections are isolated from the sparsely fractured sections with hydraulic plugs. Where hydraulic conductivity of the rock is higher, for example near the surface and in the presence of fractured zones, the backfill is designed to have high erosion resistance. The backfill design is adapted to the surrounding conditions by designing it to have a similar conductivity as the surrounding bedrock. Where the rock is sparsely fractured and hydraulic conductivity is low, the backfill is tight, again mimicking the hydraulic conductivity of the rock. The backfill is not designed to have lower hydraulic conductivity than the bedrock. Groundwater chemistry changes with depth, which is considered in the material selections, for example by considering that as the dilute water may cause bentonite erosion limits the use of bentonite clay in upper facility volumes. Mechanical plugs are used to implement backfill in different times in different facility sections, so backfill and still open facility volume are isolated from each other until the open side is also backfilled. As closure progresses mechanical plugs (Figure 23) are needed for the described installation purposes and they do not have long term performance requirements, unlike the hydraulic plugs (Figure 24) that aim to restrict groundwater movement along the tunnel. Near ground level the unintentional intrusion into the facility is hampered with intrusion obstruction plugs. In closure design, the long term safety is considered with all EBS components in mind, which limits the use of some potential materials (chemical compatibility between EBS components). The closure design aims at finding the right materials for varying conditions in the bedrock.

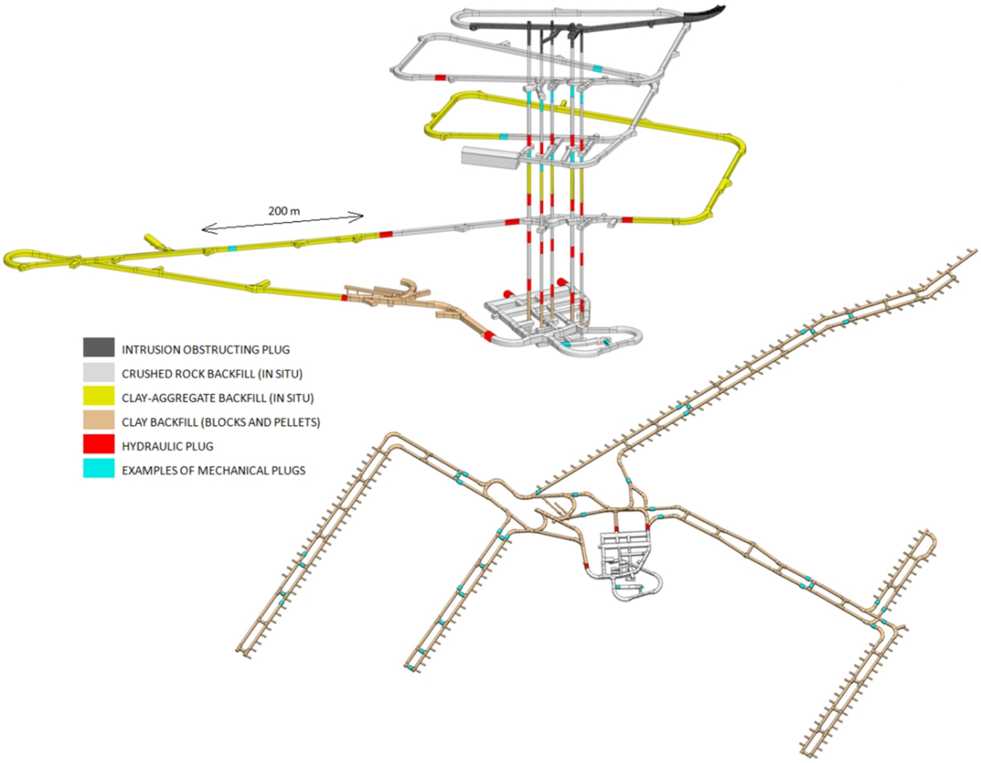


Figure 22. *A general illustration of Posiva's disposal facility layout option showing backfills and plugs for regions beyond the spent fuel repository; lower figure includes central tunnels but deposition tunnels and holes are excluded. A detailed closure design is presented in Closure Production Line report, Sievänen et al. (2012).*

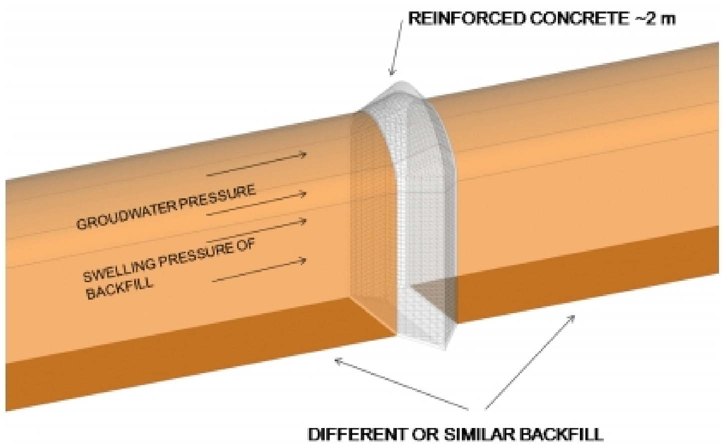


Figure 23. *An example of a mechanical plug (Dixon et al. 2012).*

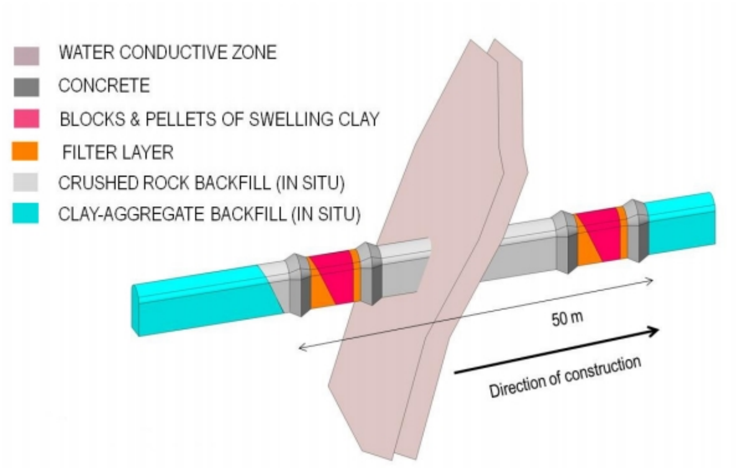


Figure 24. An example of two hydraulic plugs on both sides of a tunnel section that intersects a hydraulic zone (Dixon et al. 2012).

In the closure concept rock bolts will remain where needed. All organic materials (e.g. plastic) will be removed to avoid microbial activity. The aim is to remove shotcrete too, as well as many other concrete structures done to facilitate operations. The dismantling operation of the underground facility will be designed in detail closer to the beginning of closure, but it is already taken into consideration during building stage by designing structures not only to perform correctly during operation phase, but also to be as well removable at the end as possible (in some areas some shotcrete may have to be left in place due to occupational safety reasons). ONKALO and the final repository have strict foreign material limitations that dictate what materials are accepted for use in there and which are strictly forbidden. All materials intended for use need to be evaluated and approved before they can be used in the underground facility. Foreign material estimations are updated in regular basis, see Karvonen (2011) for the latest report.

The emphasis in Posiva's closure design is to provide such structures that help to restore the geological conditions at site after closing of the facility. This includes the closure of underground openings as well as sealing of the investigation boreholes (Sievänen et al. 2012). Closure design itself does not contain monitoring plans.

Posiva Oy has an ongoing monitoring programme at Olkiluoto site. The current monitoring plan consists of the period before the operational phase (Posiva 2012a) and further monitoring plans will be detailed closer to operational phase. Monitoring will be continued through operational phase and closure, but currently there is no plan on how the site will be monitored after closing of the facility. The main idea is that the monitoring planned for the operational period can be continued after closing of the facility, at least before the closure of the last investigation boreholes. In Posiva's current monitoring design the stop of monitoring after closure is not due to technical reasons, but due to closure designed as such it should not need monitoring.

Current monitored aspects on the site include:

- Rock mechanics (including continuous microseismic monitoring, measurement of relative movement of bedrock blocks by GPS, and precise levelling techniques, as well as extensometer and convergence measurements in excavated spaces). EDZ has not been monitored, but its continuity is estimated e.g. using ground penetrating radar. Temperature, visual tunnel monitoring.
- Hydrology and hydrogeology (groundwater pressure and flow measurements)
- Geochemistry (analysis of hydrogeochemistry employing multi-packered drillholes)
- Foreign materials (to control and register the foreign materials, some of which will be removed prior closure, introduced into the repository and other underground facilities either deliberately or accidentally over the whole construction period)
- Environmental monitoring (for evaluation of the environmental impact of the construction work, and modelling of the migration and radiological effect on the biosphere of potential releases from the repository over a very long time span)

Posiva's monitoring programme is consistent with the generic approach described in the Preliminary MoDeRn Monitoring Workflow (see Section 4.2.8 below).

4.2.2 Spent nuclear fuel repository, Forsmark, Sweden

In Sweden, SKB has have submitted the applications to build a deep geological repository in crystalline rock in Forsmark. The material produced by SKB to support the application includes description of the design, production and initial state of the closure (SKB 2010). In SKB's approach backfilling material is uniform from one underground opening to another and the block and pellet method is implemented in large scale throughout the facility (SKB 2010). The facility has been divided into the three main areas: 1) main tunnel and transport tunnels, 2) central area and access tunnel, and 3) shafts. The closure principles for access tunnel and shafts, as well as main and transport tunnels are based on the deposition tunnel backfill solution (Figure 25). In Figure 26 design details for ramp and shafts are illustrated.

Since the latest design (2010) SKB has done new work in relation to alternative designs for closure of the final repository regarding closing ramps, shafts and investigation boreholes. Luterkort et al. (2012) have studied alternatives to the reference design (SKB 2010a) in order to see if the current requirements are too strict. Based on the SKB's latest safety assessment SR-Site it has been indicated that more simplified closure solution (especially regarding ramp, shafts and borehole seals) might be feasible for Forsmark deep geological repository. The work of Luterkort et al. (2012) focused on assessing long-term safety impacts of alternative designs.

Based on the studies of alternative methods Luterkort et al. (2012) have proposed a new reference design for sealing of ramp and shafts: *"The ramp is filled with swelling clay in the form of blocks and pellets or only pellets from the repository level and 100 m upward. Between 100 m above the repository level and 50 m below ground level, the ramp is filled with crushed rock. The uppermost part of the ramp is filled with stone blocks of varying size. The fill is then injected with concrete grout. The shafts are filled with crushed rock that has been optimised for low hydraulic conductivity, from repository level all the way up to the top seal."*

They also conclude that:
"This concept is judged to meet the requirements on long-term safety. At the same time, the concept is judged to be the most cost-effective solution and the alternative that requires the least transport and thereby has the least environmental impact. Installing crushed rock instead of swelling clay in the shafts is also judged to be more robust and entail lower risks in

production and installation of the seal. This needs to be verified by further studies and tests, however.”

Luterkort et al. (2012) have also identified a number of issues that on their opinion require further in-depth studies and/or continued technology development. As the most important issues they report:

- *Description of initial state.*
- *Methodology for showing and verifying that proposed solutions meet stipulated requirements.*
- *Handling of water, including the inflow of water to those parts of the ramp where bentonite fill has been installed and handling of water coming from the part of the ramp that has not yet been filled.*
- *Technology development and demonstration for sealing of shafts with crushed rock and with bentonite (it is also judged that installing crushed rock instead of swelling clay in the shafts is more robust and entail lower risks in production and installation of the seal, but that this needs to be verified by further studies and tests).*
- Technology development for borehole sealing, including showing how crushed rock can be installed and inspected.
- Detailed plan for sealing of the repository level, including preliminary plug positions. This might affect the layout of the final repository on repository level.
- *Plugs: design to meet the stipulated requirements and ensure the long-term function of the concrete plugs.*
- *Rock support: to what extent should shotcrete be removed before sealing is done, considering e.g. the working environment.*

These are specific for Forsmark site and SKB’s closure design, but considering MIU closing project, bullet points above marked with *italics* may be of interest.

- SKBs closure design has an alternative approach, compared to Posiva, that relies more on the use of the deposition tunnel backfill type; the main reasons in selecting a different method than Posiva may rely on one hand on the differences in regulatory demand and on the other hand on the thinking that closure may be planned in detail later on and that the current plans are good enough for the time being. Sweden has less strict regulatory requirements for closure, whereas in Finland closure components are defined as part of EBS and have specific requirements. SKBs facility construction at the Forsmark site has not yet begun, which means there is still substantially less data on the bedrock characteristics of the repository site compared to Posiva’s site; Olkiluoto. Posiva has constructed an underground research facility, ONKALO, at the repository site. This facility will be part of the disposal facility, and it has already provided detailed data on the site characteristics.

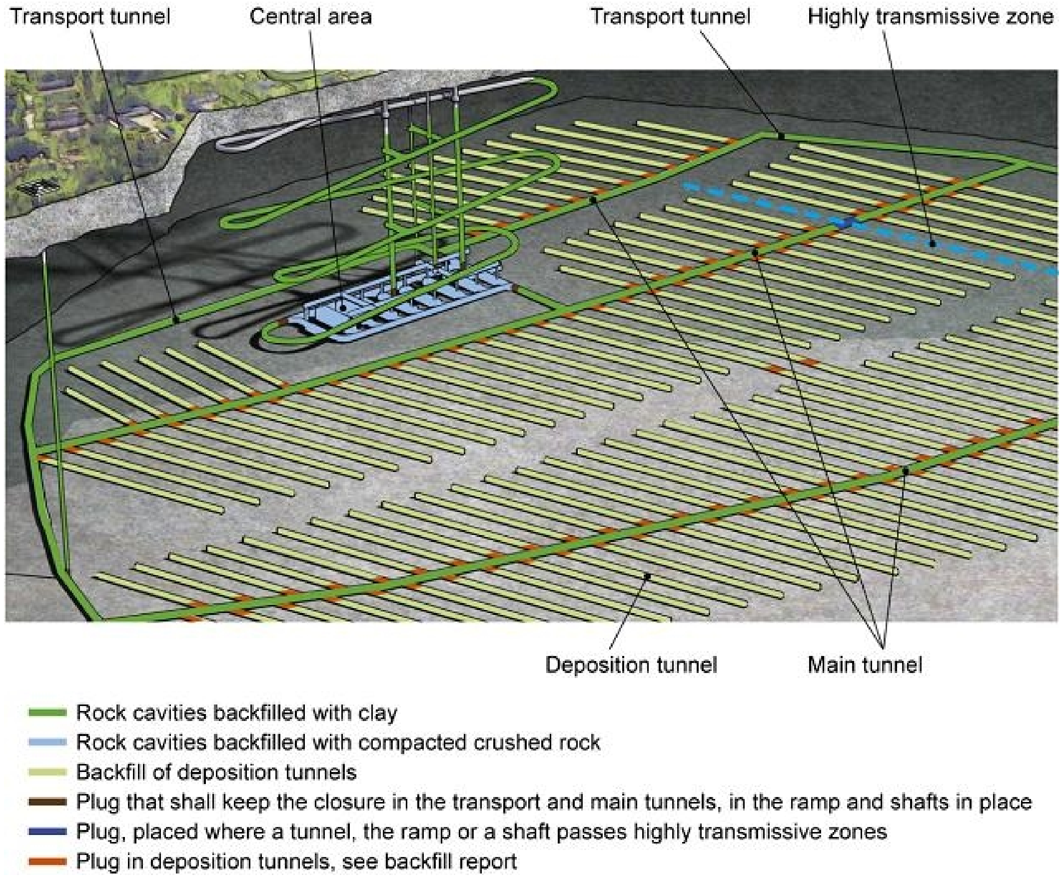


Figure 25. *Outline of the SKB reference design for closure of main and transport tunnels and the central area (SKB 2010a).*

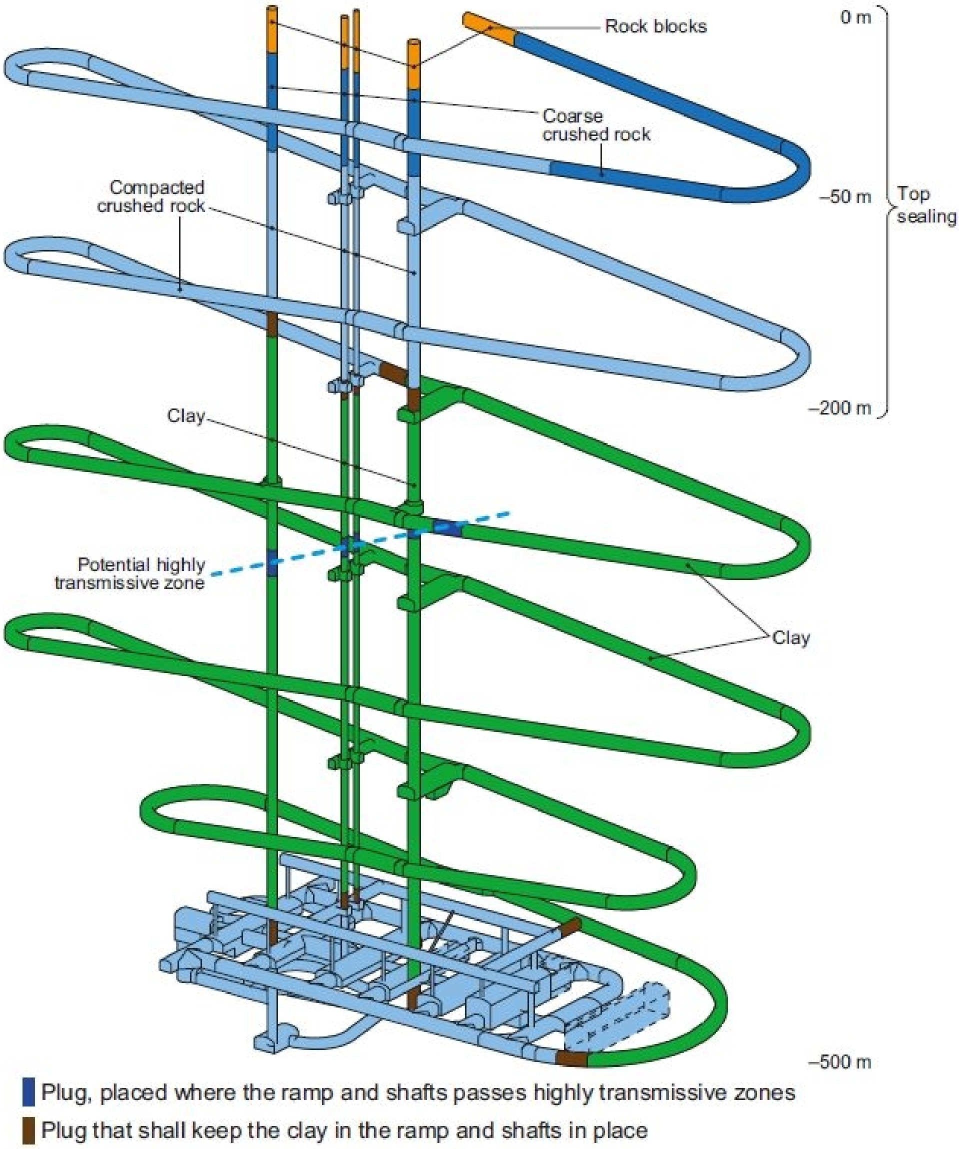


Figure 26. *Details of the SKB reference design for closure of ramps and shafts (SKB 2010a).*

4.2.3 Äspö URL Sweden

Äspö URL was built during 1990–1995. The experimental work done at Äspö is a continuation of the work that was previously pursued in the Stripa Mine in Bergslagen. Overview of Äspö URL is given in Figure 27. In this section, two main closure related tests are discussed, Prototype Repository and Backfill and Plug Tests (BPT). It is worth noting that at the moment a newish experiment, Multi Purpose Test (MPT), is ongoing, where various monitoring systems for component performance are used (also wireless) (see for general description SKB 2014, a separate report describing the installation of the monitoring systems in being compiled, but has not been published yet). MPT is specific to the KBS-3H method. However, no results have yet been published on MPT. MPT includes manufacturing of full-scale components, assembly and deposition of a supercontainer and distance blocks, as well as installation of a compartment plug with associated filling components (SKB 2013a). The deposition drift, excavated at -400 m level to better resemble disposal conditions in deep geological repository, and the components are instrumented so that the initial course of events can be monitored (SKB 2013a). It is planned that the test will be dismantled after monitoring allowing sampling and analysis of the bentonite (SKB 2013a).

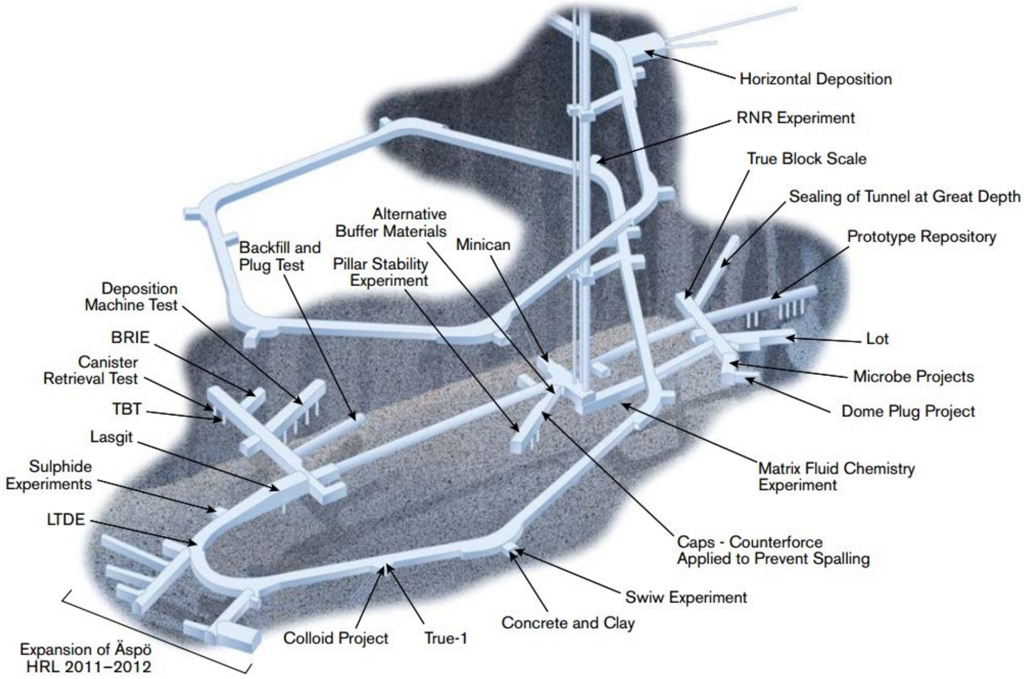


Figure 27. Overview of Äspö URL.

The Prototype Repository project aimed at testing the entire disposal concept with buffer, backfill and plugs. This full-scale test was conducted in ÄSPÖ URL and partly with European commission funding and part of it was done as joined operation SKB - Posiva. The test was carried out with 6 heated canisters in deposition holes drilled in TBM tunnels. Backfill used in the experiment was a mixture of crushed rock and bentonite. There were two sections in the test, which were separated from each other by a cask concrete plug. The outer section was dismantled after approximately 10 years with several nuclear waste organizations participating in the project. Monitoring reports have been published regularly (e.g., Goudarzi 2012 and Goudarzi & Johannesson 2009) and materials have been investigated by Olsson et al. (2013). The more recent results of the Prototype Repository are expected to be reported later in 2015.

Äspö has been the site for another plug experiment also. Backfill and Plug Test (BPT) was started in 1999 and is still in place in 2014 (Figure 28). This test aims at examining the interactions between crushed rock-bentonite mixture and the surrounding rock, as well as testing installation techniques and materials. At the back of the tunnel there is a concrete wall and backfill was then installed as inclined layers. A concrete dome shaped plug was constructed at the mouth of the tunnel. The monitoring and measurement results from the period 1st June 1999 up to 1st January 2007, except for the relative humidity, are published (Goudarzi et al. 2008).

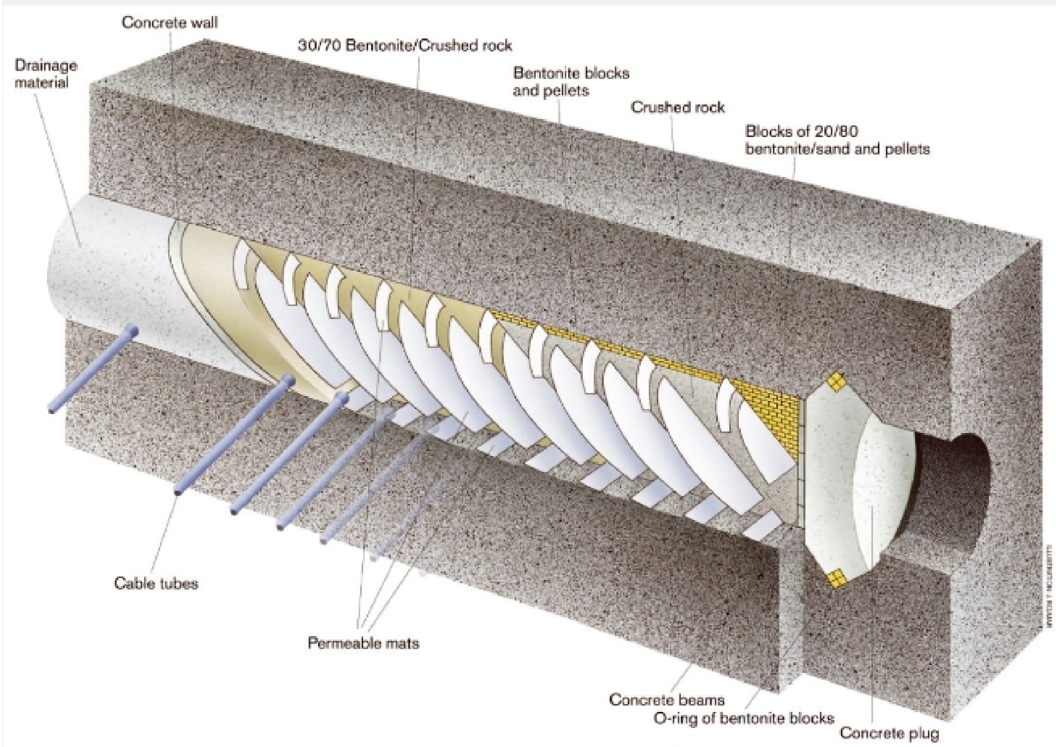


Figure 28. *Backfill and Plug Test in Äspö, Sweden (SKB 2010b).*

4.2.4 Canada URL

Canadian URL in Pinawa, Manitoba, was operated from 1982 to 2006 by Atomic Energy of Canada Limited (AECL). The facility was closed by allowing natural flooding of the URL, and in this context an experiment was conducted on construction, monitoring and performance of shaft seals in the Enhanced Sealing Project (ESP) (Dixon et al. 2009; Martino et al. 2011; Dixon et al. 2012).

In ESP two shafts leading underground were plugged with the intention to:

- Verify the ability to construct such plugs
- Monitor hardening and shrinkage of concrete parts of the plugs
- Test the mechanical strength of the concrete parts of the plugs (pressure test)
- Test the plugs sealing capacity.

The plugs were constructed in two shafts leading to URL. The smaller diameter shaft plug was left unmonitored, but the larger diameter shaft plug was equipped with monitoring for tension, temperature, water pressure, water consistency, pore pressure and total pressure in different plug components and different parts of the plug. The structure of both plugs is similar: two concrete structures and in the middle a sealing layer of in-situ compacted mixture of swelling clay and sand (Figure 29). The plugs are situated on both sides of a significant hydraulically conductive fracture, which divides the bedrock section in two different environments according to e.g. salinity; in-between the plug there is a sealing clay layer. The environmental changes were also monitored from surrounding boreholes. The plugs were built in 2010 and monitoring program was compiled for the three following years. Part of the sensors would still function but it is not known if more data of the site will be reported in the future.

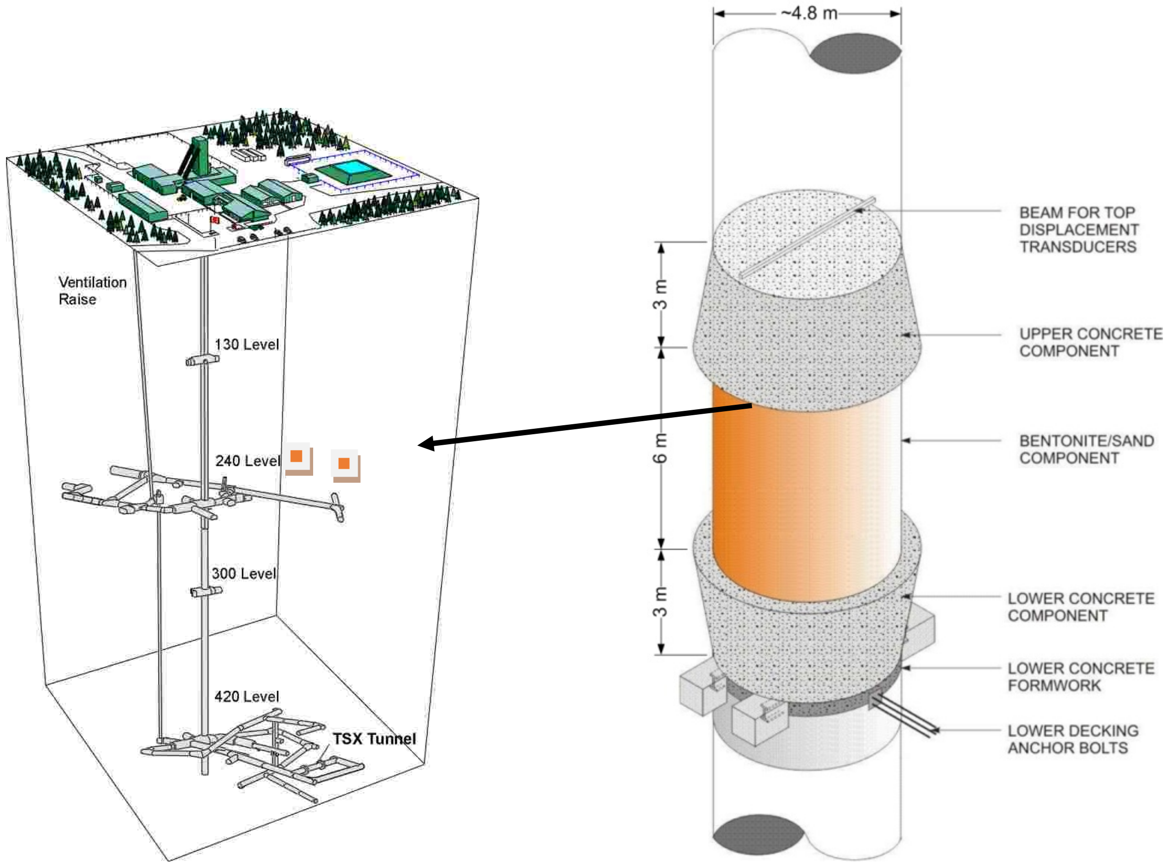


Figure 29. ESP structure and location, and location of TSX, modified from Martino et al. (2011).

Tunnel Sealing Experiment (TSX) was performed before decommissioning of the AECL URL. TSX was constructed in a tunnel and included a concrete bulk head, after that a 12 meter tunnel section with sand fill for test pressuring and then another plug constructed of bentonite-sand mixture blocks. The location of TSX is indicated in Figure 29 and TSX structure is illustrated in Figure 30. TSX test was conducted in three stages: first the test chamber between plugs was pressurized with water, then water was heated at bulk heads and circulated, and finally a three month period was allowed for cooling before the test was dismantled. The test was conducted as a building experiment, to verify performance of the materials and to observe potential leaking and endurance of plugs and also material properties and changes with elevated temperatures (Chandler et al. 2002; Martino et al. 2008.)

Both ESP and TSX have been performed as joint projects. In ESP NWMO, Posiva, SKB and Andra were involved, and TSX was performed by AECL, JAEA, Andra and WIPP.

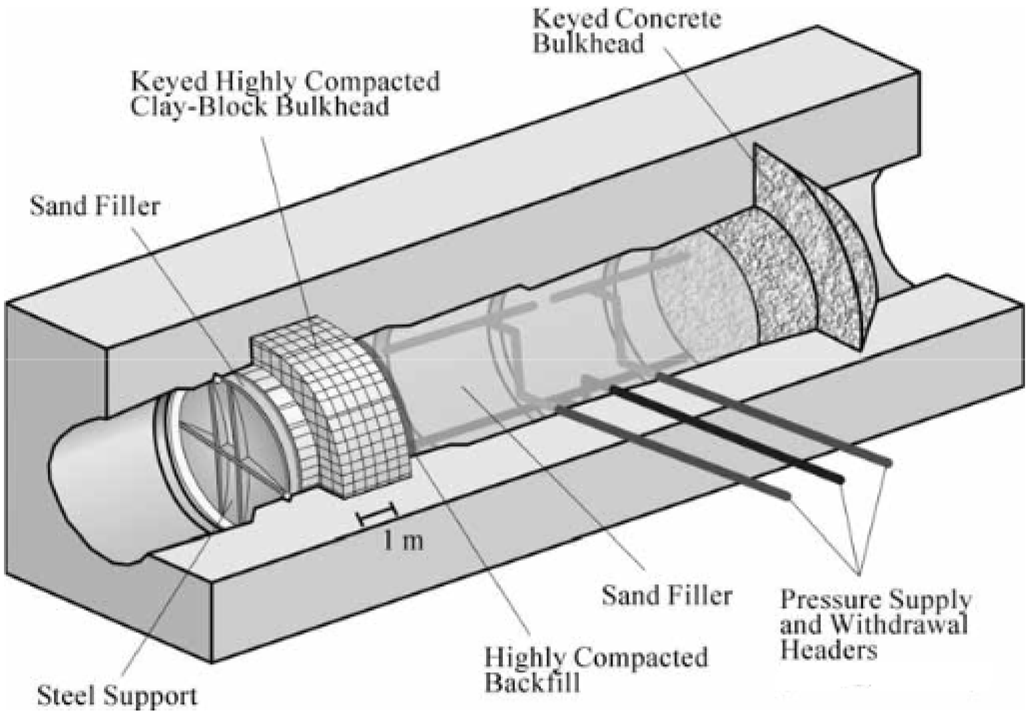


Figure 30. *TSX structure, modified from Martino et al. (2008).*

4.2.5 Cigéo Repository, France

Andra, the French national radioactive waste management agency, has established a site between communities of Meuse and Haute-Marne. This facility, Cigéo, is designed to house waste with radioactivity levels and half-lives that prevent their safe, long-term disposal in surface facilities or in the near-surface disposal facility also studied by Andra. This is long-lived intermediate level waste (LL-ILW) and high-level waste (HLW), which consists mainly of spent fuel and/or vitrified residues arising from spent fuel reprocessing operations.

The Meuse and Haute-Marne site is a sedimentary site with a succession of layers of limestone, marl and argillaceous rock deposited in ancient oceans. The disposal is designed to be done to the argillaceous layer, which is homogeneous and very thick (more than 130 m) (http://www.andra.fr/download/andra-international-en/document/editions/504va.pdf).

After operational phase Cigéo will be closed gradually according to decision making processes. The current design is to use excavated argillaceous clay that has been stored at ground level in backfilling the facility volumes, and use plugs with concrete structures and sealing swelling clay layer to isolate facility sections.

Schematic closing plans for Cigéo repository are illustrated in Figure 31.

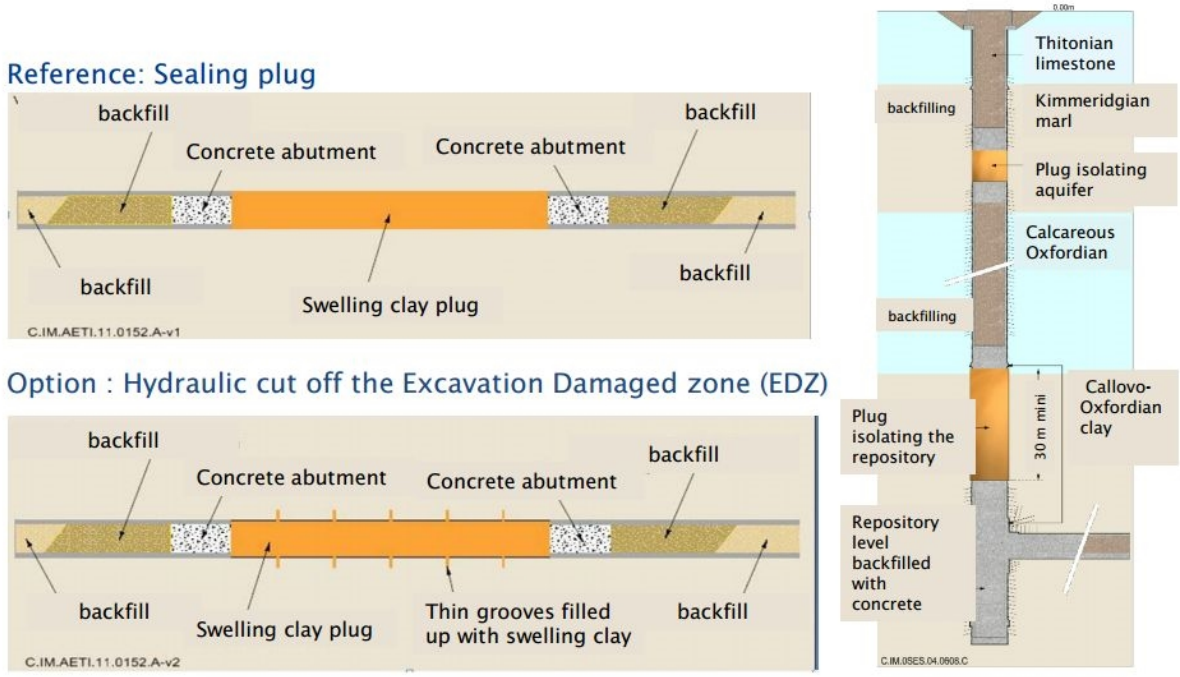


Figure 31. Sealing and backfilling of access shaft, horizontal drift or LL-ILW disposal vault at Cigéo repository, France (http://www.lucoex.eu/files/WS-ASPO/GeneralpresentationoftheCIGEOproject_Jean_MichelBosgireaudl.pdf).

4.2.6 DOPAS

Full-Scale Demonstration of Plugs and Seals (DOPAS) is a project funded by the European Union's European Atomic Energy Community's (Euratom) seventh framework programme and it includes a set of full-scale underground demonstrations, laboratory experiments, and performance assessment studies (subprojects) in different countries and by different implementing nuclear disposal companies. The subprojects are performed under the large scale DOPAS program to acquire funding and to disseminate information of the tests. The project is still ongoing and only part of the subprojects have proceeded to monitoring stage. The subprojects and test location countries are:

1. Posiva Plug (POPLU), Finland
2. Dome Plug Experiment (DOMPLU), Sweden
3. Experimental Pressure Sealing Plug (EPSP), Czech Republic
4. Full-scale seal (FSS), France
5. ELSA, Germany.

In POPLU an alternative for a deposition tunnel plug is demonstrated and as such a steel reinforced concrete wedge plug will be constructed in ONKALO URCF. Construction of the plug is due to start during 2014. Behind the approximately 6-m-long plug there is modified backfill (bentonite) for facilitating the testing of plug in the desired way. POPLU is designed to:

- provide information for the selection and excavation of plug location,
- provide information for the implementation of construction methods with qualified working methods and quality assurance in ONKALO conditions,

- provide a possibility to monitor the concrete plug behaviour during and after casting, and
- facilitate the evaluation of the mechanical strength and hydraulic sealing properties of the concrete plug.

After testing results are acquired, they are compared to modelled results and comparison will be published together with other DOPAS deliverables. POPLU is illustrated in Figure 32.

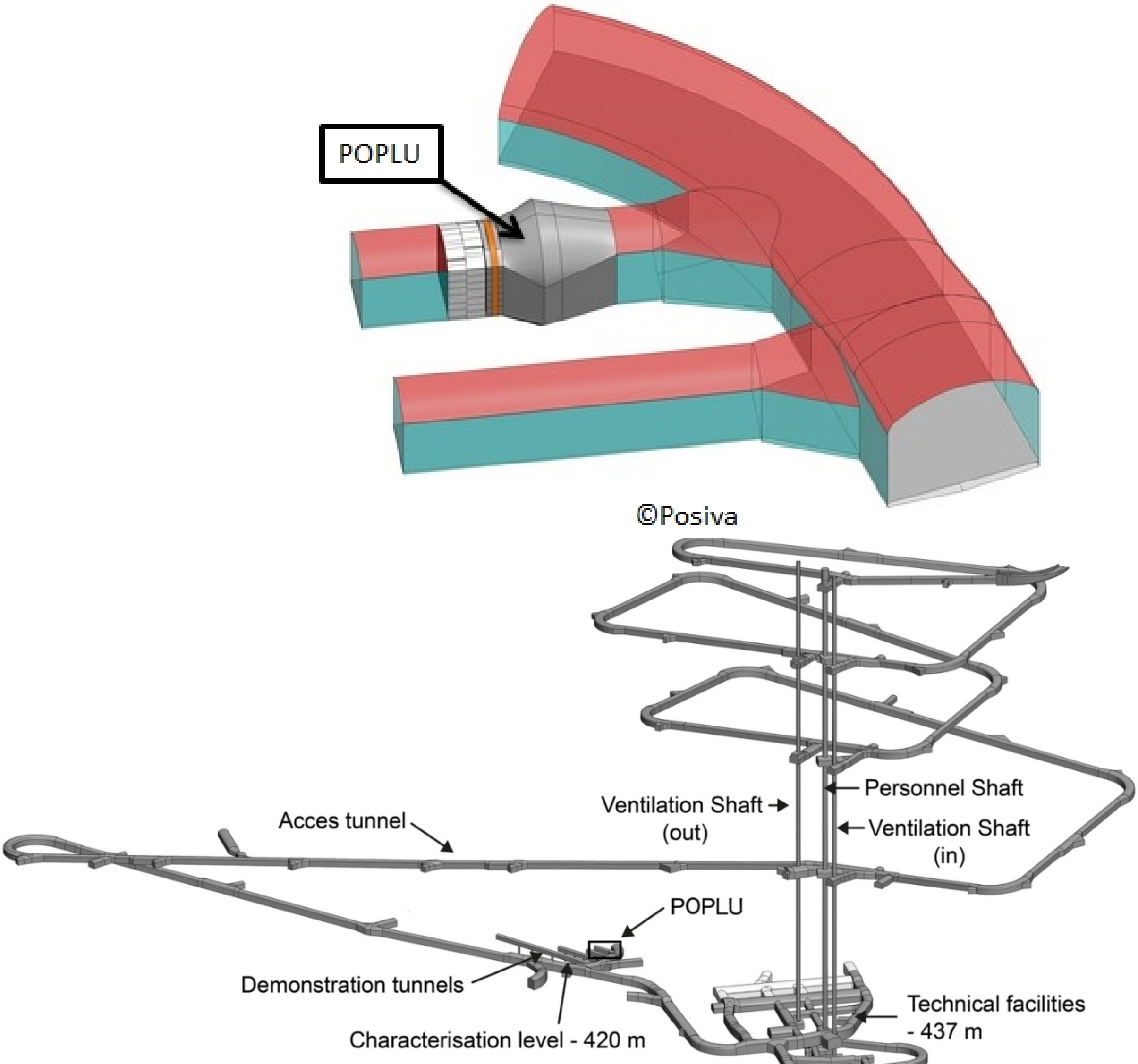


Figure 32. Illustration of POPLU (modified from http://www.posiva.fi/dopas).

DOMPLU is a deposition tunnel plug demonstration in Äspö URL. It is a dome shaped plug without reinforcement. It was designed during 2011 and field work was initiated 2012, followed by the plug construction in spring 2013. The plug and rock interface has been grouted and the plug is being monitored for its hydraulic sealing properties and mechanical stability. DOMPLU is illustrated in Figure 33.

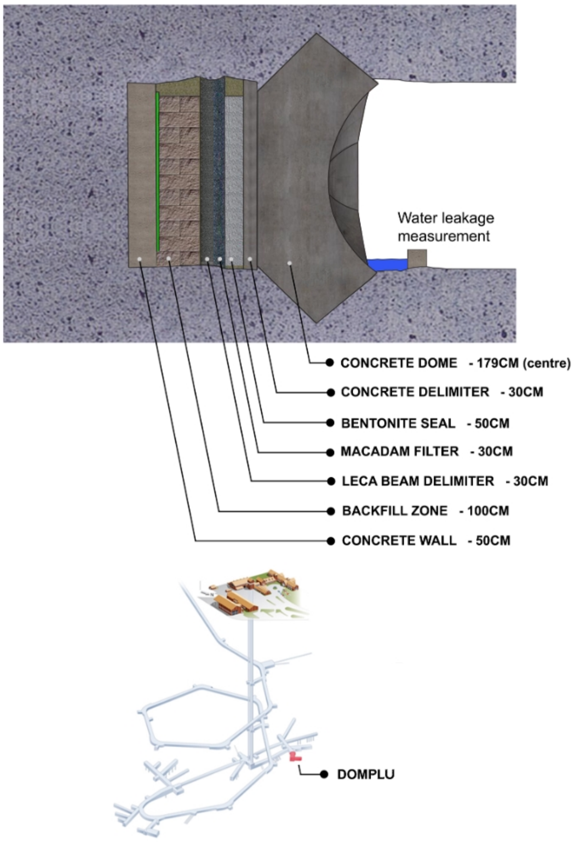


Figure 33. *Illustration of DOMPLU (modified from http://www.posiva.fi/dopas).*

FSS is a tunnel closure experiment done by Andra on ground surface as a full-scale demonstration in concrete-build tunnel mock-up. It has three main components: a cast concrete plug, a shotcrete manufactured plug and bentonite pellet section with swelling capacity between them. The aim of the project is to assist design work of hydraulic plugs with main attention on the development of installation methods and implementation and quality control in achieving initial state for the materials. FSS is illustrated in Figure 34.

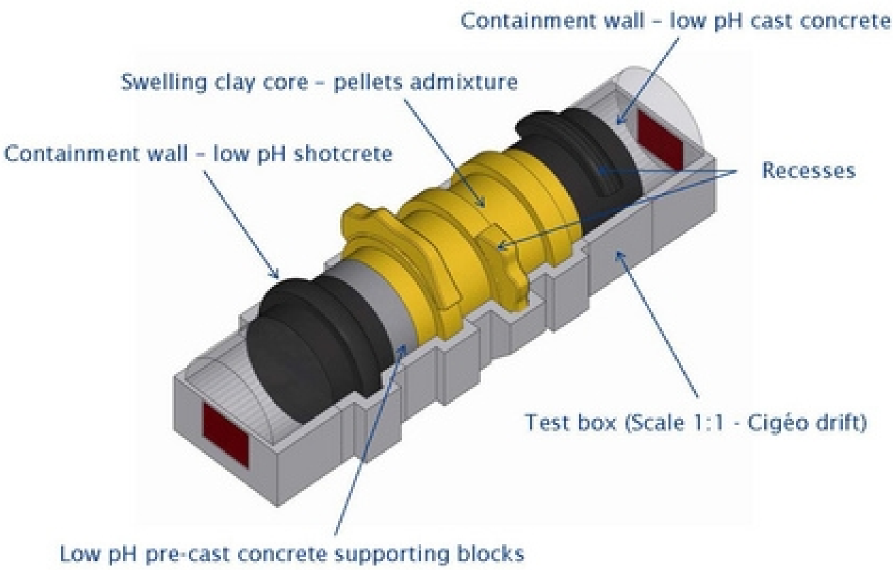


Figure 34. *Illustration of FSS (http://www.posiva.fi/dopas).*

EPSP is also a full-scale experiment with two shotcreted plugs and a bentonite pellet intermediate. ROKLE formation bentonite is used (local material) in bentonite pellets and ice is used in installation to produce moisture for pellets. The main aims of the plug test are to investigate the possibility to use experimental materials and methods in installation and to monitor resulted performance of the plug structure. EPSP is illustrated in Figure 35.

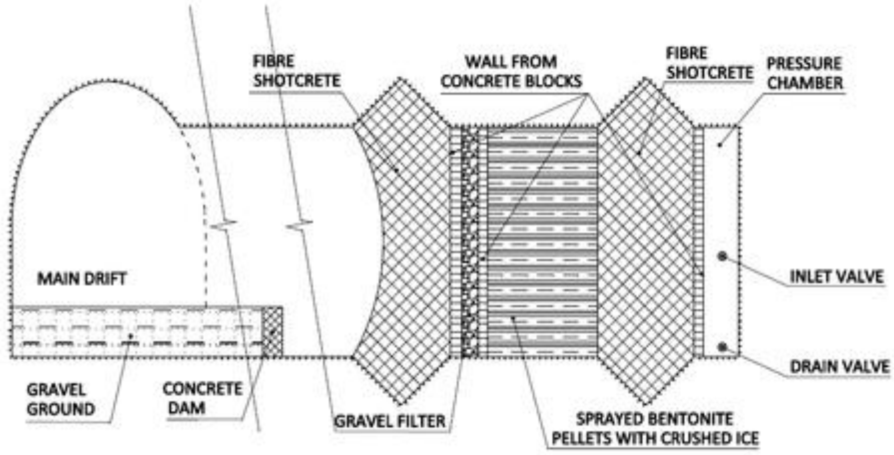


Figure 35. *Illustration of EPSP (http://www.posiva.fi/dopas).*

ELSA includes laboratory and in-situ experiment with an aim to experiment construction of shaft seal in salt rock formation. Design of the plug is not yet in public distribution. The project has three phases, of which the second one is currently under way (in September 2014):

- Boundary conditions and requirements for shaft seals in salt and clay host rocks.
- Development of shaft seal concepts and testing of functional elements of shaft seals in laboratory tests and in small-scale in-situ tests, including testing and calibration of mathematical models of material behaviour.
- A large-scale demonstration test of particular sealing components and adjustment of the sealing concept. The main requirements of the test are to demonstrate technical feasibility and long-term effectiveness. It has not yet been determined which components will be tested within this phase of the ELSA project.

There are two internet sites where DOPAS project can be followed: http://www.posiva.fi/dopas and http://www.igdtp.eu/index.php/european-projects/dopas. Deliverables will be published at the end of the project in 2016.

4.2.7 LUCOEX

LUCOEX (Large Underground Concept Experiments) project is a joint project between Posiva, Andra, SKB and Nagra. The objective of the four year LUCOEX project is to: *"demonstrate the technical feasibility in situ for safe and reliable construction, manufacturing, disposal and sealing of repositories for long-lived high-level nuclear waste (www.lucoex.eu)."* The demonstration activities in the project take place in four different underground research laboratories (URL) in Europe (Mont Terri, Äspö, ONKALO and Bure), which have been constructed for the specific purpose of developing repository technology under repository-like conditions. The demonstrations include four different concepts. Most of the installation tests concern EBS components in the near-field, but some tests also include closure components, such as backfill materials and plugs. Experiences within LUCOEX show that the demonstration is essential part of the feasible emplacement of any materials in repositories.

Installation is not straight forward, especially when design is novel. Thus, in case of Mizunami, considering the time constraints, the techniques employed should be for the most part such that these have been already tested.

During e.g. LUCOEX project is has been observed that also storing of the materials need to be organised very well in order to be able to produce components that will produce the desired initial state and fulfil requirements. For MIU closing test it is important to set requirements against which the emplacement and closing will be performed. This will provide valuable experience on how to perform emplacement, what kind of processes are involved and how they need to be integrated. Initial state is also vital to reflect the monitoring results during the monitoring period.

4.2.8 MoDeRn

MoDeRn (Monitoring Developments for Safe Repository Operation and Staged Closure) was an international collaborative project (18 partners from the European Union, the United States of America, Japan and Switzerland) with an objective *"to take the state-of-the-art of broadly accepted, main monitoring objectives, to develop these to a level of description that is closer to the* ***actual implementation of monitoring*** *during the staged approach of the disposal process, to verify whether such implementation is able to address* ***expert and lay stakeholder expectations****, to provide an understanding of* ***monitoring activities*** *and* ***available technologies*** *that can be implemented in a* ***repository context****, and to provide recommendations for related, future stakeholder engagement activities.* (www.modern-fp7.eu)*"*

An overall approach for developing monitoring programme is illustrated as a work flow in Figure 36.This overall approach has been followed e.g. when developing Posiva's monitoring plans (see Section 4.1).

The MoDeRn project has focussed particularly on monitoring of the near field (White 2013). Some studied monitoring systems are more promising regarding closure monitoring. In principle the emphasis has been on developing wireless systems. Regarding repository closure, the long-term safety aspects limit a lot what can be done regarding monitoring equipment implementation. However, in URLs, also to be closed, these requirements are not so strict, and maybe some wire systems could also be accepted. However, regarding gaining experience for the future, wireless systems need to be developed.

Most interesting topics reported in MoDeRn (White 2013) are:
- Seismic tomography sensing (e.g. for saturation) tested at Mont Terri and Grimsel (ETH Zurich & NDA 2013)
- High frequency nodes (e.g. water pressure), however these are developed only for short distance monitoring
- Also optical fibre sensor systems have provided promising results in URLs (not maybe applicable in real repository)
- Low frequency wireless transmission, which holds potential for longer distance transmission of data (hundreds of meters)

In the case studies performed within MoDeRn it has been advised that for some cases monitoring for the repository could be done by using dummy emplacement. In this frame of thinking, MIU could be considered also as a dummy closure, and thus wire systems could also be advisable.

In general MoDeRn's most valuable input lies in the monitoring strategy development, rather than solving in technical challenges in the monitoring technologies.

FEP based strategy development provides transparent and comprehensive approach for monitoring strategy development. In Figure 36 this is illustrated in a box called “identify processes to monitor”. The usability of FEP approach depends on the main objectives of the project and reasons for monitoring. In MIU case it might be that not all processes and parameters that would be monitored for real repository need to be included. Also in MIUs case, potential international collaboration might produce FEPs that are not common to a given disposal concept or safety assessment/ safety case.

In MoDeRn also stakeholder communication has been seen as of importance, which is especially relevant in countries where site selection process in still ongoing.

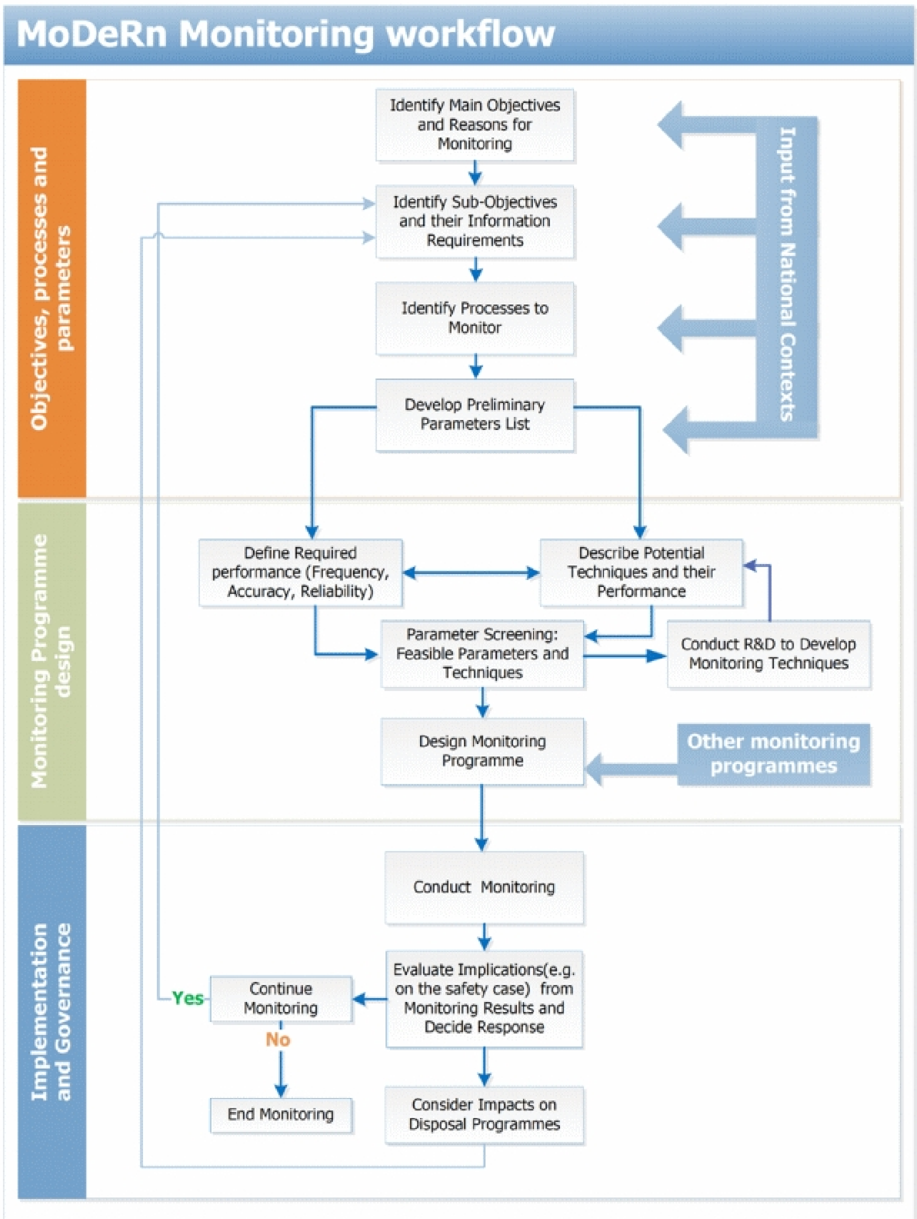


Figure 36. MoDeRn monitoring workflow (White 2014).

4.2.9 Other disposal projects

Although the scope of this report lies within crystalline environment HLW repositories and their closure with emphasis on advanced projects, it is relevant also to review sedimentary environments and plans to close repositories planned at lower depths (i.e. LLW and ILW waste repositories). This is of interest, as the sediments at higher level in MIU need to be accounted for in the closing plan for MIU and there is potential also to test technical closure solutions in sedimentary environment. Cigéo for HLW was already discussed in Section 4.1.5 and few other examples are discussed below.

In Belgium HLW is designed to be disposed into local clay formation, Boom clay. HLW disposal has been investigated in Hades URL in Mol. Hades is a rock laboratory constructed in Boom clay to the depth of -225 m. Closure design for Hades is not available.

In Switzerland the use of Opalinus clay is investigated for use in HLW disposal. Mont Terri URL is constructed to limestone, dolomite, marl and clay formation and the site is being used only for investigation purposes and will never hold any radioactive waste material. Closure design for Mont Terri is not available. Most of the Mont Terri investigations have been tracer investigations, hydraulic investigations in clay (borehole techniques and monitoring), and demonstrations of disposal process phases or engineered barrier components.

4.3 Geological and hydrogeological/chemical conditions around tunnels

Geological and hydrogeological conditions around disposal sites, candidate sites for disposal or URL sites, which MIU is, vary depending on the local geology. In addition to the baseline conditions, also excavation techniques and grouting criteria in order to control inflows affect greatly the overall boundary conditions. In Table 4 the main parameters from two relevant projects that have used the site specific information in planning of closure have been compiled.

In addition to these baseline conditions the evolution of the sites has been considered. For example, in Fennoscandia glaciation and permafrost conditions need to be accounted for when designing closure components, especially close to bedrock surface.

In experimental set ups, where closure components have been tested (such as those listed in Section 4.1) host rock conditions have also been observed and analysed, but depending on the objectives of individual demonstrations and experiments the level of detail varies.

Regarding closing Mizunami URL, the main emphasis is on closing the whole facility and hence the examples from full closure designs are of main interest.

Table 4. *Geological and hydrogeological conditions around underground openings considered in the design and testing of closure systems; based on data by Posiva Oy, Finland and description of the site properties at Forsmark, Sweden.*

Project/ location	Geology	Hydrogeological conditions	Salinity	Redox conditions	Note	References
Posiva-Olkiluoto	Crystalline fractured rock	Hydraulic conductivities (K), sparsely fractured rock: 0 - 50 m: K_H=1E-07 m/s* , and K_V=1E-08 m/s* 50 -100 m: K= 3.2E-08 – 5E-09 m/s** 100 – 200 m: K= 5E-09 – 1.3E-10 m/s** 200 – 300 m: K= 1.3E-10 m/s 300 – 400 m: K= 1.3E-10 m/s 400 – 500 m: K= 3.0E-11 m/s 500 – 2000 m: K= 3.0E-11 m/s Transmissivities (T), fractured zones: HZ19, about 100 m depth: T up to 1E-05 – 1E-04 m^2/s HZ20, about 300-400 m depth: T up to 1E-05 m^2/s	TDS from meteoric to saline (around 10 g/L, max 30 g/L). More saline waters present at deeper levels and these have been accounted for in design.	Anoxic, except shallow levels (down to -40m).	Design for disposal site. Controlled inflows. Closure concept adapted to site properties and relevant scenarios.	Sievänen et al. (2012) Posiva (2012) Dixon et al. (2013)
SKB-Forsmark	Crystalline fractured rock	Hydraulic conductivities as modelled for Forsmark. SKB's design premises denote: *"Below the location of the top sealing, the integrated effective connected hydraulic conductivity of the backfill in tunnels, ramp and shafts and the EDZ surrounding them must be less than 10–8 m/s. This value need not be upheld in sections where e.g. the tunnel or ramp passes highly transmissive zones."* + *"There is no restriction on the hydraulic conductivity in the central area."* + *"The top sealing has no demands on hydraulic conductivity."*	TDS from meteoric at shallow depths up to ~16 g/L TDS at depth. Salinity increases with depth.	Integrated evaluation shows that the rock/water system (including microbial activity) maintains a buffer capacity that ensures a reducing character at depths greater than 100 m	Underground openings not excavated yet. General design for closure.	SKB (2010a) (SKB 2013b) (Laaksoharju et al. 2008) SKB (2008)

*For the depth interval 0-50 the hydraulic conductivity is anisotropic; the horizontal component K_H being 10 times higher than the vertical component K_V.
**The logarithm decreases linearly with depth.

4.4 Closure production

In relation to closing of the facilities, procedures, materials and schedules need to be defined. Production of closure aims at producing closure with pre-defined properties at the initial state. These properties are set as requirements.

As mentioned above, full closing tests have not been done anywhere in the world in relation to HLW repository, nor is there an URL where a total closure with full backfilling would have been done. Detailed plans have been produced during the design of closing the planned repositories in Finland and Sweden, but these have not been demonstrated. This is due to the timing of the closure in many decades away from the present time, and hence, the emphasis has been on demonstrating the EBS components closer to HLW canisters (that is, buffer, backfill and plugs for deposition tunnels). However, this does not mean that it would not be important to demonstrate closing in full scale, and at least in Finland and Sweden the start of closure tests and demonstration is close at hand. Many smaller scale and component specific demonstrations give a good idea on how different materials behave and there is also some experience on installation of the closure structures form the tests of deposition tunnel backfill and plugs done so far.

In general, closing of the repositories or larger parts of them is planned to be done as a continuous operation after emplacement of the waste and related components. However, due to the large volumes to be filled, and due to strict requirements for the quality it is foreseen that the closing operations of the underground spaces between the deep geological repository and the ground surface will take several years.

Materials for the closure vary depending on the project, but in general the overall design consist of concrete plugs (Ordinary Portland Cement, OPC, or low-pH cement) and backfill materials that contain swelling component for places where tight contact with the surrounding bedrock is required.

An overview of the procedures, materials and schedules is given in Table 5. In Table 6 the tests and demonstrations related to closure done prior 2012 are summarized (Dixon et al. 2012).

Table 5. *Summary of closure concepts and test set ups, with main materials and status or schedules.*

Project/ location	**Closure concept**	**Materials**	**Schedule/Status**
Posiva-Olkiluoto repository (Finland, including ONKALO URCF)	**General closure design:** Both in-situ and block and pellet methods employed. Also options such as shotclay are mentioned to be potentially usable.	Variable, materials selected to reflect the surrounding properties (i.e. hydraulic conductivity) of the host rock accounting their long-term durability. Plugs are used to isolate conductive features. Also some plugs (mechanical) are used for operational purposes. Borehole plugging planned for investigation holes, observation equipment are removed prior closure of the holes.	Step-wise implementation during period of tens of years, starting from central tunnels at repository level. Closing will start when first repository panels are full. Note that operational period lasts about 100y. However, apart from deep repository level tunnels the closing of shafts and access ramp will be done after emplacement of all waste.
SKB-Forsmark repository (Sweden)	**General closure design:** Block and pellet method, pre-compacted pellet filling Also option for in-situ compaction	No direct aim to follow host rock properties. Design is done to close deep situating volumes with tight backfill that is similar in all tunnels, and use backfill with less/no hydraulic requirements in central area and top seal. Borehole plugging planned for investigation holes.	Closure will take place after disposal of spent fuel. During operation only deposition tunnels will be backfilled and plugged.
Äspö URL (Sweden)	No full closure. **BPT:** In situ compaction of backfill, concrete plug installation. **Prototype repository**: in-situ backfilling and self-compacting concrete plug. **MPT**: artificial wetting demonstration for horizontal emplacement.	**BPT:** also 20/80 bentonite/sand blocks and bentonite pellets. **Prototype repository:** 30/70 bentonite/crushed rock backfill material. **MPT:** bentonite in test for horizontal placement (KBS-3H)	Mid-tem large scale tests. **BPT:** Dismantling remains undefined **Prototype repository:** I Stage dismantled and reporting in 2014 **MPT:** Test started, to be dismantled after monitoring.
Project/ location	**Test set up**	**Materials**	**Schedule/Status**
Stripa mine (Sweden)	No full closure. Plug test site.	Plug tests (ordinary cement based concrete with bentonite components). Borehole plugging tests.	Finalised.
Canadian URL (Whiteshell laboratories)	Flooding of facility with groundwater, no full backfill.		URL left flooded. Finalised.
	ESP: Hydraulic plug in shafts. **TSX:** Plug and backfill materials.	**ESP:** Low-heat high-performance concrete with steel framework, in situ compacted bentonite/aggregate mixture (40/60). **TSX:** 30/70 Bentonite/crushed rock backfill, crushed rock backfill, concrete plugs	**ESP** left in place. **TSX** dismantled.
DOPAS: POPLU (Finland)	Deposition tunnel plug with limited and modified backfill (wedge shaped plug)	Low-pH cement, steel reinforcement	Construction in 2014-2015. Dismantling in 2016.
DOPAS: DOMPLU	Deposition tunnel plug (dome shaped plug)	Low-pH cement	Constructed, monitoring phase ongoing in 2014-2015.

(Sweden)			Dismantling in 2016
DOPAS: EPSP (Czeck Republic)	Hydraulic plug in tunnel	Low-pH cement (shotcrete), Rokle bentonite pellet and crushed ice mixture	Construction in 2014, monitoring through 2015, and dismantling in 2016.
DOPAS: FSS (France)	Horizontal drift seal, surface mock-up experiment in full-scale	Bentonite pellets, low-pH concrete (cast and shotcreted)	Construction in 2014, monitoring through 2015, and dismantling in 2016
DOPAS: ELSA (Germany)	Hydraulic shaft plug in salt rock formation (project mainly concerning laboratory investigations and design of experiment)	Several material investigations included in project, including e.g. salt, basalt and MgO concrete.	Design stage. Component testing ahead, without large scale system test

Table 6. *Laboratory studies and fieldwork conducted before 2012 concerning materials and methods that can be considered in relation to MIU closure, modified from Dixon et al. (2012, Table 4-1). After these publications (prior 2012), DOPAS project and Prototype repository results will offer new information for possibilities in the closing of MIU, but publication is still awaited for.*

Subject	Details	Reference
Backfill	**Material Evaluation and Design Studies**	
Design & selection	Summary of work done as part of Posiva/SKB joint project Baclo III	Keto et al. 2009
Design & selection	Evaluate deposition tunnel backfill options	Hansen et al. 2009
Design & selection	Buffer and Backfill process report (SR-Can)	SKB 2006
Materials	Review of potential alternative backfill materials and installation methods	Dixon and Keto 2008
Materials	Material parameter effects on backfill compaction	Keto et al. 2006
Materials	Material properties evaluation	Johannesson & Nilsson 2006, Johannesson 2008
Materials	Wetting and homogenization of backfill	Johannesson et al. 2008
Materials	Erosion & sealing of backfill, lab testing	Sandén et al. 2008
Materials	Buffer and backfill materials properties	Pusch 2002a,b, 2003
Concepts	Evaluation of alternative materials and means of installation	Gunnarsson et al. 2003, 04, 06, Börgesson et al. 2009
Concepts	Block option	Keto & Rönnqvist 2006
Concepts	In situ compaction option	Keto 2006
Backfill	**Field-Scale Studies**	
Demonstrations	Water uptake & flow through block-pellet mock-ups	Riikonen 2009
Demonstrations	Water uptake and flow through block-pellet mock-ups	Dixon et al. 2008b, 2011
Demonstrations	In situ compaction trials	Korkiala-Tanttu et al. 2007
Demonstrations	Half-scale mock-up of block and pellet tunnel backfilling	Dixon et al. 2008a
Demonstrations	Prototype repository	SKB 2009
Demonstrations	Backfill and Plug Test	Goudarzi et al. 2008 SKB 2009
Demonstrations	Shaft backfilling	Dixon et al. 2009 Martino et al. 2011
Demonstrations	Deposition tunnel backfilling, block placement	Wimelius & Pusch 2008
Plugs	**Laboratory and other evaluations**	
Materials	Effects of grouting, shotcreting and concrete on backfill geochemistry	Luna et al. 2006

Subject	Details	Reference
Materials	Concrete durability	Martino 2006
Plugs	**Field-Scale Studies**	
Demonstrations	Tunnel Plug Test Stripa Mine	Gray 1993
Concepts	Low pH concrete plug	Dahlström et al. 2009
Concepts	Low pH self-compacting concrete plug	Vogt et al. 2009
Concepts	T-M analysis of plug for deposition tunnel	Fälth and Gatter 2009
Demonstrations	Plug II in Prototype Repository Äspö	Dahlström 2009
Demonstrations	Backfill and Plug Test	SKB 2009
Demonstrations	Prototype Repository	SKB 2009
Demonstrations	Tunnel Sealing Experiment	Chandler et al. 2002 Martino et al. 2008
Demonstrations	Enhanced Sealing Project	Dixon et al. 2009 Martino et al. 2011 Holowick et al. 2011

4.5 Monitoring of closure

Monitoring of the site is one of the essential parts of a disposal program as well as URL projects. Monitoring needs to be started already during site selection phase and baseline data is collected prior disturbances caused by excavations. Monitoring continues during the operational period and depending on the project, it continues also after operations have been ceased.

Since there is no full scale closing experiments done anywhere to date, there is no overall experience in monitoring all the site evolution relevant aspects at a given location. However, many different properties are being monitored at various locations depending on the objective of the disposal program/URL project (see above discussions). The size of experiment, desired resolution of monitoring results, test period etc. affect the planning of the overall monitoring scheme. In addition to site monitoring, also closure performance monitoring is of importance, especially during demonstration of the system performance.

Posiva, in Finland, has the most advanced monitoring programme related to actual disposal site and hence it covers a wide variety of monitoring targets. The objectives set for the Olkiluoto monitoring program are (Posiva 2012a):

- **Long-term safety (site)**. Demonstrating that the conditions in the surroundings of the repository remain favourable for long-term safety despite repository construction and operation.
- **Feedback to site characterisation and modelling**. Acquiring data that can be used to define and test various models of the surroundings of the repository, which increases the understanding of the site and its evolution.
- Monitoring the **environmental impact**.
- **EBS performance**. Monitoring the performance of the engineered barrier system to confirm the basis for expected/predicted behaviour.
- Providing **feedback for construction and design** on the **impact of construction** on the geosphere and surface environment.
- **Compulsory radiological monitoring**. Conducting the mandatory monitoring of radiation and of releases of radioactive substances in the environment of the repository.

In Table 7 targets for monitoring reflecting the list given above are presented with indication on the resolution of data acquisition. Also examples of layouts in relation to target processes are given.

Table 7. Compilation of monitoring practices. Example from repository site in Finland (Posiva 2012a).

Target	Resolution - Monitoring period
Rock mechanics 1. Stress redistribution 2. Fracture reactivation 3. Rock creep 4. Spalling 5. Thermal evolution 6. Isostatic uplift 7. Tectonic movements 8. Seismicity	Annual/biannual to continuous - The whole site investigation and operational period. Current detailed plans made until 2018.
Hydrological monitoring 1. Evolution of groundwater table 2. Evolution of groundwater flow 3. Evolution of hydraulic properties in the bedrock and the over-burden 4. Evolution of hydraulic head 5. Inflow to tunnels 6. Evolution of groundwater salinity distribution 7. Influence of above ground freshwater reservoir 8. Perturbation of surface hydrology	Hourly, daily, weekly, monthly, yearly depending on the monitoring (see Table 5-2 in Posiva 2012a). - As above.
Hydrogeochemical monitoring 1. Evolution of groundwater properties and salinity distribution in shallow groundwater 2. Evolution of groundwater properties and salinity distribution in deep groundwater 3. Influence of above ground freshwater reservoir 4. Influence of foreign materials 5. Inflow to tunnels (chemical analysis) 6. ONKALO URL process water monitoring 7. Leaching from rock spoil	For most there is yearly plan. See Table 6-2 in Posiva (2012b). Sodium fluorescein, EC and pH measurements done weekly from process water. - As above.
Monitoring for surface environment	High. Serves Biosphere Assessment and Environmental Assessment. See chapter 7 in Posiva (2012a) - As above.
Monitoring of foreign materials 1. Use of foreign materials (amount) 2. Influence of foreign materials in process water 3. Influence of foreign materials in groundwater	For 1. there is continuous follow-up. For 2. weekly by EC, pH monitoring, four times per year regarding GW samples. A separate plan is flowed in case of 3. (detailed gw sampling). - As above.
Monitoring of the EBS (canister not included here) Backfill: 1. Heat transfer 2. Water uptake 3. Swelling 4. Mass redistribution 5. Chemical changes in porewater Plugs: 6. Degradation	Depending on the demonstrated EBS component. - Posiva is aiming to establish a monitoring programme for the engineered barrier system (EBS) before the start of the operation of the repository, as demanded by the regulations.

4.6 Feedback for MIU closure

Up to date, closure components have been tested and demonstrated within various emplacement and demonstration projects, some of which are mentioned above. Many components have also been studied in detail for tens of years in relation to their overall long-term performance.

Also full closure designs have been developed within the two advanced disposal programmes in Finland and Sweden. These both have been analysed also as a part of the safety cases.

Detailed monitoring systems have been developed for disposal sites and within URL experiments.

Despite of the vast amount of information, there is very limited amount of experimental information on the full scale closure of deep geological repositories. Also regarding practices for production, there is very little practical experience. In addition to technical challenges, there is a lot of targets for development introduced, e.g. in MoDeRn project.

There are several demonstration projects ongoing with a first priority to demonstrate the applicability of design in practice (see above sections discussing especially the DOPAS and LUCOEX). This is needed since the operational practices need to be tested and performance demonstrated before the operational phase; this is foreseen to take place e.g. in Finland around early 2020's.

Quality Assurance is also a topic currently discussed in many countries. In a larger scale project QA becomes more demanding due to large amounts of materials.

Site scale closure sets some constraints on to what can be monitored after closing the facility because the accessibility is lost after closure. Also, as closing is meant to be final, there are no dismantling operations planned (retrievability is planned as to be possible but not planned to be done).

Regarding monitoring of the performance of the closing components, such as plugs and backfill, it may be undesirable to install wiring systems in the facility (in case aiming to not introduce new foreign materials and connections to ground surface). However, in a purely experimental case, such as MIU, this might be an option. Another way is to install wireless monitoring systems but, these as well, may have many technical challenges. Wireless monitoring systems have been successfully used in FEBEX and currently in use e.g. in MPT test. Technical issues should be solved prior to installing any monitoring systems and their functionality should be assured to be such that the project results will match the investment made.

Settling of the backfilling materials should be minimised in the closing solutions since the aim is to produce such a filling that no continuous paths are created between the deep geological repository and the ground surface. In general it can be said that in-situ backfilling may be more prone to settling problems than the block/pellet method. This issue is discussed by Dixon et al. (2012) referring to the Äspö Backfill and Plug Test (BPT):

"The 30/70[1] backfill installed in the BPT is a good demonstration of the advantages and disadvantages of in situ compaction of backfill as inclined layers, highlighting some of the issues related to inflowing water during backfill emplacement and also the potential for compartment backfilling. A higher permeability fill (crushed rock) was placed in a section

[1] 30% bentonite/ 70% aggregate.

where installation of a low permeability backfill would be unnecessary and then a carefully engineered concrete plug was installed in a location where two sections of tunnel having different hydraulic requirements meet."

And, that:

"In the BPT the potential for a crushed rock fill to settle, and thereby generate an open gap at the crown of the tunnel was dealt with through use of a bentonite component at the upper part of the tunnel. Information gained from both of these backfill placement demonstrations has direct relevance to backfilling where in situ compaction is considered."

Selecting the right locations for plug structures is one of the most important things when building plugging systems that have the objective to act as hydraulic barriers. Wrongly placed plug will not be effective if the groundwater circulates in the area in the surrounding bedrock more effectively than in the plugged section, as was seen already in the Stripa mine experiments (Gray 1993). At Stripa tunnel plug test the test plug was located in pegmatite, with several steep dipping fractures that were connected to each other. When water was pumped into the test structure to produce pressure and test sealing ability of the components, the connected bedrock fractures resulted in leakage of about 90-95% of in-pumped water to flow past one of the plugs concrete components and into the water sumps installed to collect seepage water. As a conclusion it is not reasonable to install plugs in highly fractured bedrock, as the plugs in these environments would leak around the plug. In short term, isolation is better achieved by grouting the fractures. This kind of a solution may be needed at some point in closure to facilitate for example waiting times between continuing backfilling operation. In long term, grout may eventually degrade and thus tunnel plugging is not a long term solution for highly fractured rock.

Site scale hydrogeological and hydrogeochemical monitoring is somewhat easier since despite of closing the underground openings the borehole based monitoring is easy to continue.

All the topics discussed above call for further experiments, and closing MIU has all the potential for increasing knowledge on the implementation of closing systems as well as monitoring of the closure components behaviour and site evolution.

Based on the experiences from the international programmes the following is recommended:

- Overall plan for closure, i.e. ideally technical design for MIU closure should be based on specific geological and hydrogeological conditions. This means that,
  - o the hydrogeological features of the site need to be used as a main guideline when selecting the closure concept and materials for closure
  - o requirements need to be set for closure and other boundary conditions should be defined
  - o specific research themes need to be identified, accounting for the potential given by MIU site.
- The plan should include both monitoring of the site and monitoring of the closure component performance
- The plan should be such that it demonstrates closing of a repository, and at the same time provides final safe closure solution for the URL.
- Since the plan concerns ULR experiment, which would be first of its kind, international interest is certain. International research theme for MIU should be presented, in order to use the results of this report in the further steps in the project.

- Related to the design and implementation, it would be recommended that mostly tested emplacement techniques would be used, due to limited amount of time, but schedules permitting, limited amount of testing, however, could possible and of interest.
- QA practices should be developed and tested in practice.

5 Strategy and plans for closing the Mizunami URL

5.1 Strategy

The MIU facility will be closed using backfilling concept, materials and techniques resulting in a closure solution that meets the specified requirements set (see below) for the performance.

The closing strategy has three main goals:

1. to close the underground research laboratory permanently in a robust manner and to implement site specific design (see Section 5.4),
2. to conduct experiments (including monitoring) before and during the closure operation in order to utilise the full potential for scientific research on site (see Sections 5.5 and 5.6), and
3. to provide such closure of the facility that the land can be used safely by the local municipality after closure.

The strategy will be put in action following a step wise plan (Figure 37). This is needed in order to make a detailed plan and to define JAEAs detailed scale objectives for the closure project and to seek international collaboration, which is seen of great importance to achieve the best results regarding goal 2. Also, the final schedule needs to be cleared, in case there would be possibilities to extend it. This is of importance for defining e.g. site monitoring goals.

In the text below, a short overview on the implementation plan of the strategy is presented. First, the preliminary requirements are presented in Section 5.2. Secondly, boundary conditions specific to MIU case are discussed. The scientific objectives of the closure project are related to experiments, monitoring, modelling and obtaining emplacement experience. These are discussed in Section 5.6. Although the strategy proposed here aims for best possible solution and practical constraints have not been the main focus, technical challenges and constraints in relation to schedules are briefly discussed in Sections 5.7 and 5.8.

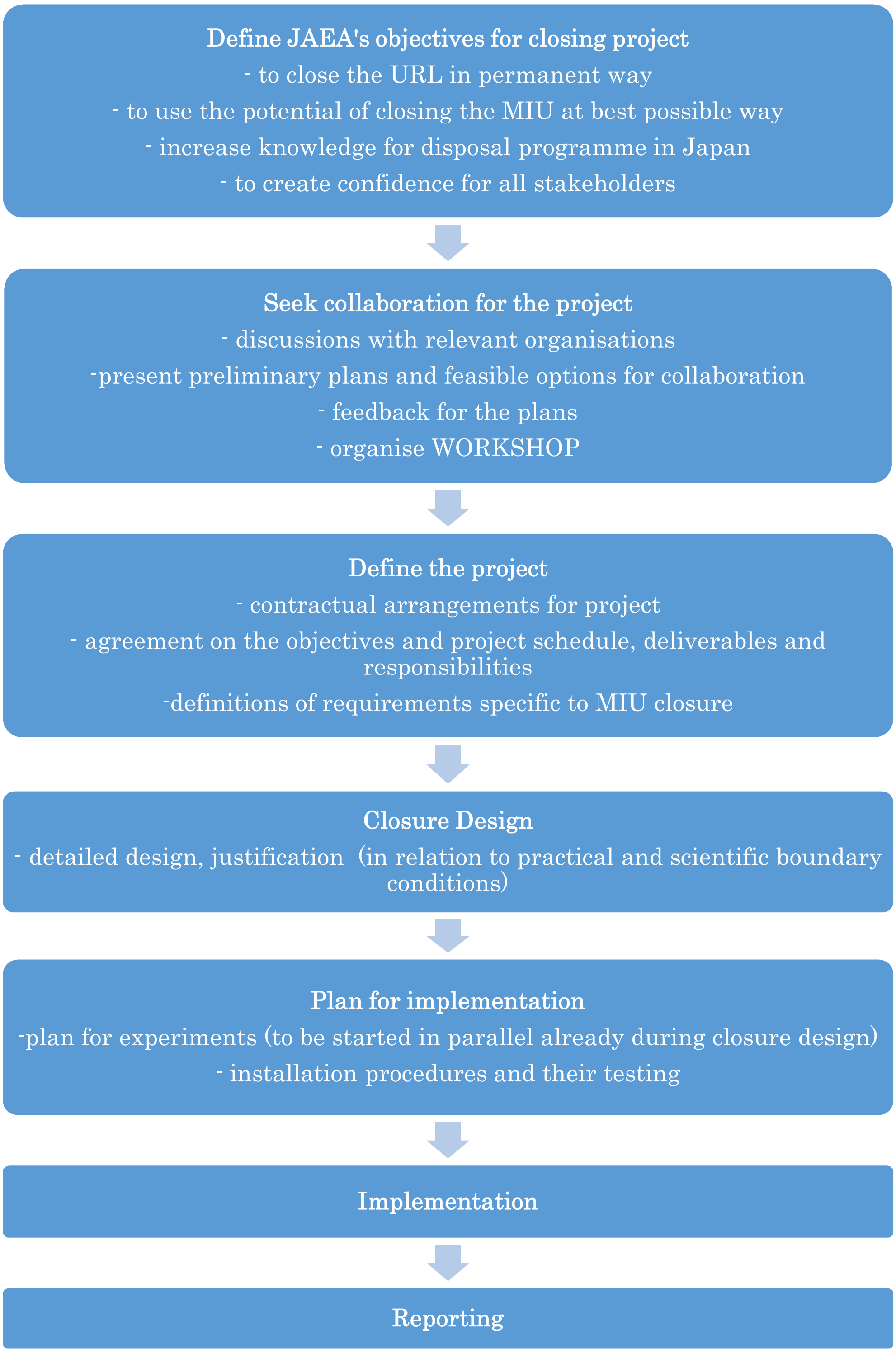


Figure 37. Step wise plan for implementing the closure strategy.

5.2 Requirements

Setting up requirements for the closure is essential in order to have a sound basis for the closure design and for assessment of the system performance. The following preliminary performance requirements are set for the closure of MIU:

1. **Hydraulic conductivity of the backfilling materials needs to be similar to or lower than the hydraulic conductivity of the surrounding rock to help to restore the natural conditions in the geosphere.**
   Justification: this requirement is based on the need to restore the baseline (especially groundwater) conditions of the site; it is one of the main objectives in long-term safety of the repositories, that underground spaces should change the natural conditions as little as possible.

2. **Closure should provide stable structures that can be left un-monitored after the end of the scientific and environmental monitoring phase.**
   Justification: this assures post-closure safety at the site.
   These are achieved by requiring, that:

3. **Backfilling shall be used (and potentially plugging)**
   Justification: backfilling contributes to the stability of the underground spaces and allows the safe future land-use. Also, closing of MIU provides an opportunity to investigate the performance of structures that are actually planned to be used in the geological repositories.

4. **Materials used shall be such that they are suitable also for geological repositories.**
   Justification: to serve to the larger community dealing with the geological disposal of nuclear waste (in line with the objectives of MIU project).
   In order to observe the functionality of the closure, the following is further required:

5. **Monitoring of the installed closure components shall be implemented.**
   Justification: to check that the components perform as expected and that the groundwater flow conditions are restored.

6. **Groundwater characteristics of the site shall be monitored before, during and after closure.**
   Justification: to obtain relevant data on the baseline, operational and post-closure conditions and to provide sufficient environmental monitoring (also scientific importance in relation to restoration monitoring).

7. **Uranium bearing formation will be hydraulically isolated from ground environment in shaft locations and material excavated from that formation will be placed back in shafts of that location.**
   Justification: This has originally been promised to the local municipality. The excavated uranium bearing rocks need to be placed in excavated shafts and the sealing performance of the above lying cap formation can be returned by using a plug structure with hydraulic sealing properties.

5.3 Boundary conditions and AIMS

Boundary conditions defining, limiting and excluding closure components and their placement in the MIU URL are derived from the site characteristics described in more detail in Chapter 3. With respect to closure the main shaft fault, sedimentary sections (due to their hydrogeological properties) and uranium bearing formation (due to previous agreement with the local government) are in key position (Figure 38 and Table 8). The hydraulic conductivities are closely connected to rock type and crosscutting features. In material selection erosion due to water flow and chemistry are included as boundary conditions.

Zone S200_13 is not included as a bounding feature. No differences in geochemistry and hydraulic conductivities have been detected on different sides of the feature in level -500 m gallery.

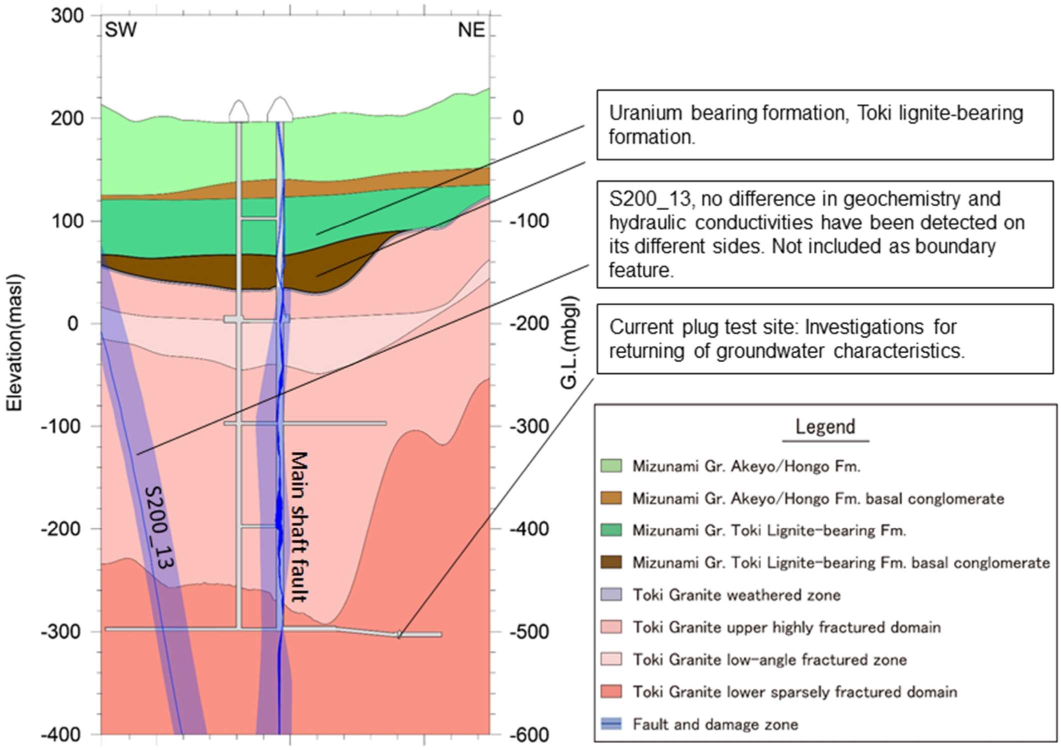


Figure 38. Main shaft fault, S200_13 and plug test site.

Table 8. Boundary conditions for closure design.

Boundary conditions for closure design
Main shaft fault (and damage zone) is a hydrogeological barrier (lower hydraulic conductivity than in the surrounding granite)
Uranium bearing formation needs to be isolated from the surface environment.
Sedimentary section contains clayey horizon that acts as a hydrogeological and hydrogeochemical barrier.

With selected boundary conditions the closure solution is designed to meet requirements with selection of materials that are compatible with the characteristics of locations they are installed into. The sealing function of the main shaft fault is returned and the uranium bearing formation is sealed from above openings. Otherwise the solution is designed to be safe, cost-effective and long-term enduring, following the set requirements. Potential investigations are suggested in Section 5.6, and these are presented as such they do not compromise the closure design and it requirements.

NB: Regarding uranium bearing Toki lignite section more detailed plan may be needed in order to check what is the phase uranium is at in the rock and what the expected redox conditions are in the surrounding groundwater. If possible, it might be also an option to place the uranium containing rock mass at the deeper parts of the facility where reducing conditions prevail as well. This might allow more precise location for the hydraulic plugs that would be installed in the shafts where the impermeable section is (dividing the two chemically different groundwater regimes).

5.4 Closure concept development

The plan presented here is designed to provide the ideal output from the closing of the MIU. Target is to plan, demonstrate and monitor a full scale closure of underground spaces, with similar requirements that are anticipated for a real repository. This includes monitoring the performance of closure components as well as long-term monitoring of the site.

A preliminary design has been compiled according to the requirements set in the Section 5.2 and boundary conditions presented in Section 5.3. Closure will include two types of components: backfill and plugs. Options are presented for potential materials. Details on structural design and backfill installation method will be completed in next project phases when closure design is more advanced from the preliminary one at the strategy phase introduced in this project.

Interesting with the MIU site is that the hydraulic characteristics differ from many of the crystalline sites studied in other programmes internationally. At the MIU site, majority of URL volumes have rather high conductivities, but the main fault at the site is relatively dry and acts as a dividing structure. On the contrary, for example in Finland the granitic/gneiss bedrock sections have low conductivities, but fractured zones (fault zones) are the main hydraulically conductive features. However, the principle in developing the closure is the same (see requirement 1 in Section 5.2).

5.4.1 MIU closure backfill

Main component in closure is backfill. Its performance is supported by plugs. The optimal backfill will follow the bedrock characteristics and in the MIU case the geology is roughly divided in four sections: sedimentary area near ground surface, uranium bearing formation, crystalline bedrock, and main shaft fault.

The main shaft fault in the case of MIU is the least conductive area of underground rooms that divides the bedrock of the site in separate hydrogeological volumes. Hydraulic conductivities within the main shaft fault in the granitic rock are around 3.2E-11 m/s (main part of the main shaft fault) and 1.0E-9 m/s (low permeability zone around main shaft fault). The reported conductivities in granitic fractured areas are 6 to 4 decades higher. In sedimentary section hydraulic conductivity of the fault zone is slightly lower, 5.0E-8 m/s.

Within the closure design four different backfill materials are needed. Tight backfill material is recommended to be used in locations where hydraulic properties of the backfill are wanted to be kept low. The volumes on either side of such isolating feature are in more conductive areas, and can be filled with material with less strict conductivity requirements, hereafter called tunnel fill.

JAEA has agreed to return the uranium bearing excavated rock back to its original location in the sedimentary rock formation (Toki lignite-bearing formation). There is thus no further discussion of this materials consistency and potential to use other materials instead, as this is a decided matter. However, consideration of the boundary between the two groundwater systems should be accounted for (impermeable layer between Toki and Akeyo-Hongo).

The sedimentary layer of rock in uppermost URL near ground surface has several options in material selection and its closure material is hereafter referred to as backfill for sedimentary rocks. This material will be installed above the area where the uranium bearing excavated rock is returned to its original volume. However, with the need to seal uranium bearing formation from ground environment, it is possible to use more conductive materials, as there will be a sealing structure below this backfill.

In plans for closure of radioactive waste repositories, the tight backfill material usually considered is bentonite clay, or mixture of bentonite clay and crushed rock (or sand/gravel) to reach desired hydraulic conductivities. These two are good options also for MIU closure and detailed design phase will decide on the exact structures and materials. Also alternative clay materials could be tested, such as non-swelling illite. The material selection containing swelling component is fairly wide, including:

- bentonite (Na- or Ca-bentonite);
- mixture of rock material and bentonite;
- swelling clay (montmorillonite content below bentonite level);
- material including non-swelling clay (mixture).

Tunnel fill is used to support tunnel structure and fill volumes to limit erosion and extrusion of tight backfill. It is also an important safety feature in considering long-term human safety for local residents as with filled tunnels the risk of plug erosion and thus falling in the filled volumes would be mitigated. Tunnel section could, in part at least, be filled with water, but for volumes next to tight backfill it will be beneficial to use a fill material to prevent tight backfill from transferring to water-filled volumes and eroding away, and in shafts to prevent collapse of surface plug structure into shaft further in the future. The fill should be designed not to sink in time (see requirement 2 in Section 5.2), to keep the shafts full and inhibit formation of potential cave-ins near ground surface. Potential tunnel fill materials (also mixtures of these are possible) are:

- crushed rock (could be excavated material also from MIU);
- gravel;
- sand;
- boulders (could be excavated material also from MIU).

In Table 9 a few examples of hydraulic conductivities of rock based materials are given. The final selection may depend on the availability and other practical boundary conditions.

Table 9. *Examples of hydraulic conductivities for different soil types and processed rock materials i.e. for different grain size distributions (Dixon et al. 2012 and references therein).*

Soil type / processed rock material	Hydraulic conductivity (m/s)
Silt	10^{-5} - 10^{-9}
Gravel moraine	10^{-4} - 10^{-7}
Sand moraine	10^{-6} - 10^{-8}
Silt moraine	10^{-7} - 10^{-10}
Well graded aggregate	10^{-5} to 10^{-7}
TBM-muck	10^{-7} to 2×10^{-10}

The sedimentary rocks consist of tighter fine grained sections and more conductive conglomerate sections. The lowermost fine grained clay rich sedimentary unit forms a hydrogeological boundary. For the sedimentary section, the backfill can be selected based on the hydrogeological properties of the rock types, similarly to the granitic parts of the system.

In regions near ground surface it could be beneficial to emphasize erosion resistance over swelling potential due to surface weathering and erosion. Concrete plugging is planned to the top most parts of the shafts that can then be landscaped on the surface.

In openings in the uranium bearing formation JAEA has agreed with the local municipality that the excavated rock will be returned to the openings. This leaves no room for discussion of the material, but it should be estimated has any material loss occurred and should an additional component be added to the rock mass to fill the volume. This addition could for example be other local rock material (sand, crushed rock). The volume of excavated rock will also need consideration on will it need further crushing for adequate compaction, so it will fit the volume as required. If excavated rock is in large pieces, it may not compact well and may take more volume than that of the openings where it is from.

5.4.2 MIU closure plugs

To fulfil the requirements for closure the backfill materials will need to maintain their performance and stay at place, for which reason plugs may need to be installed at interfaces of different backfill materials. These plugs will facilitate the slow process of saturation and maintain materials at place by taking into account swelling pressure and the potential difference in hydraulic pressures at different sides of the plugs. In certain locations hydraulic plug are needed to provide re-sealing of produced openings to natural sealing formations.

Concrete plugs needed for material support can be either dome or wedge shaped. The details of plugs will be designed in structural design phase after the strategy phase presented in this report. The function of these plugs is to act as support structures for different materials and facilitate the homogenisation of bentonite including materials and levelling of pressures on different sides of the plugs.

Hydraulic plugs would act as sealing components within the URL openings and would significantly hinder the flow of water thought the excavated and then closed openings. The structure would include a sealing layer (bentonite) and two concrete structures on its both sides. Concrete structures would cut through the EDZ. The available designs for hydraulic plugs (see e.g. Figure 24 and Figure 29) can be tailored to fit the MIU conditions at the selected location. If necessary, a filter layer may be part of the plug.

Plugs will also be built at the ground level to deprive entrance to the closed facility and to resist surface erosion and weathering. These will be installed at the mouths of both shafts. If wished, the ground area can then be landscaped. These can be simple concrete structures with landscaping on top of them.

5.4.3 MIU closure design alternatives

This report offers two alternative ways to close Mizunami URL. The first option, design alternative A, is done with the original requirements in mind. With this, the closure materials have been designed based on the idea of restoring the site properties, as discussed e.g. in Sections 4.2.1 and 4.7. The second option, design alternative B, is designed to fulfil requirements meaning in that the isolating performance of the sealing features (of main shaft fault) are designed to be similar to the original, but the material placement is done to minimise work steps and simplify the process.

There are similarities with these design options in that the uranium bearing formation will need to be cut off from the surface environment, and this is recommended in both alternatives to be done with hydraulic plugs at cap rock location. Surface structures are not discussed in detail in either option, but they are considered to be simple and similar in both options.

In both designs A and B the transition from tunnel fill to excavated rock approximately at the depth of -170 m in the ventilation shaft, where rock type changes, is envisioned to need a concrete plug between materials. However, there is no natural hydraulic barrier at the boundary of the two rock types and thus a potentially constructed plug would not have any significant sealing performance. The reason for this plug would only be to diminish mixing of the two backfill materials as it has been promised that the excavated material would remain in the formation from where it was excavated off. Therefore it is possible to implement this plug with quite little effort in comparison to other plugs, just by casting a firm concrete bed for the excavated rock to lie on firm base, so it will not slowly sink in between possible pore space within tunnel fill material in shaft below. If tunnel fill is dense enough there may not be need for this concrete plug at all.

The plug test site at -500 m level can be left as it is in both alternatives and tunnel behind the plug flooded, unless JAEA has other interests in dismantling the test.

It is possible that as closure is implemented, temporary plugs need to be used for safety purposes and to keep already installed backfill in place during a time when backfilling is continued at another location. This is especially the case if both tunnels are closed at the same time. For example, one shaft is closed to the depth of -400 m but before continuation of the backfill, the other shaft is being backfilled. There may be need to use temporary shields to keep the backfill in place then. The need and design of these potential plugs will be done after the decisions on the implementation strategy and deriving the schedule and plan for the closure operation.

1) Design alternative A.

Design alternative A is presented in Figure 39.
The design utilizes:

1. Tight backfill in main shaft fault location.
2. Concrete plugs to support tight backfill.
3. Concrete plugs in both shafts below uranium bearing formation.
4. Excavated rock returned to uranium bearing formation.
5. Hydraulic plugs in cap rock, above uranium bearing formation.
6. Tunnel fill in all other openings (granitic rock).
7. Several options in filling shafts above hydraulic plugs of cap rock.
8. Plugging and landscaping of surface site.

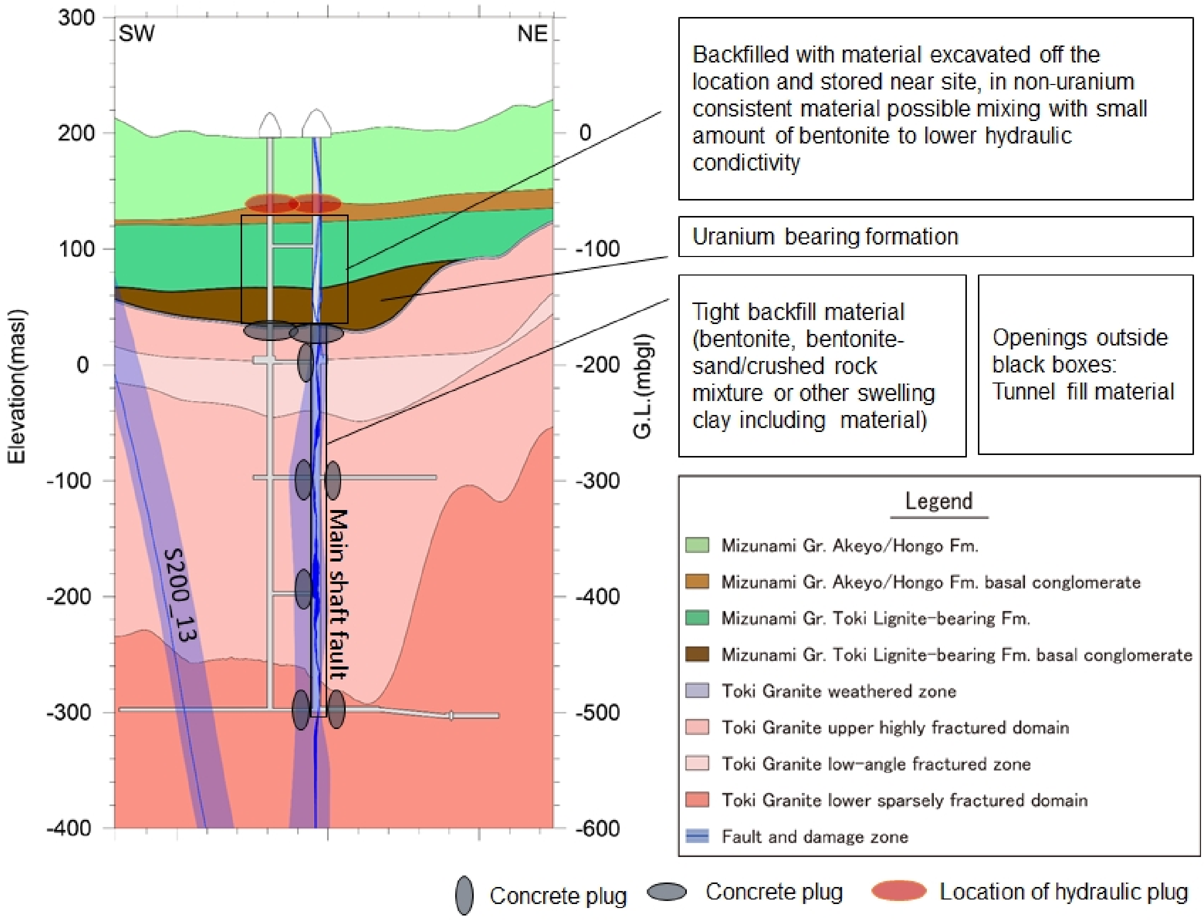


Figure 39*. Mizunami URL closure design alternative A.*

<u>2) Design alternative B.</u>

Design alternative B is presented in Figure 40. The design utilizes:

1. Hydraulic plugs in galleries to seal openings through main shaft fault and disturbed zone. Three dimensional hydraulic plug in main shaft, where the entire fault has been cut through by the shaft and gallery (using concrete plugs and tight backfill).
2. Tunnel fill in all other openings (granitic rock).
3. Concrete plugs in both shafts below uranium bearing formation.
4. Excavated rock returned to uranium bearing formation.
5. Hydraulic plugs in cap rock, above uranium bearing formation.
6. Several options in filling shafts above hydraulic plugs of cap rock.
7. Plugging and landscaping of surface site.

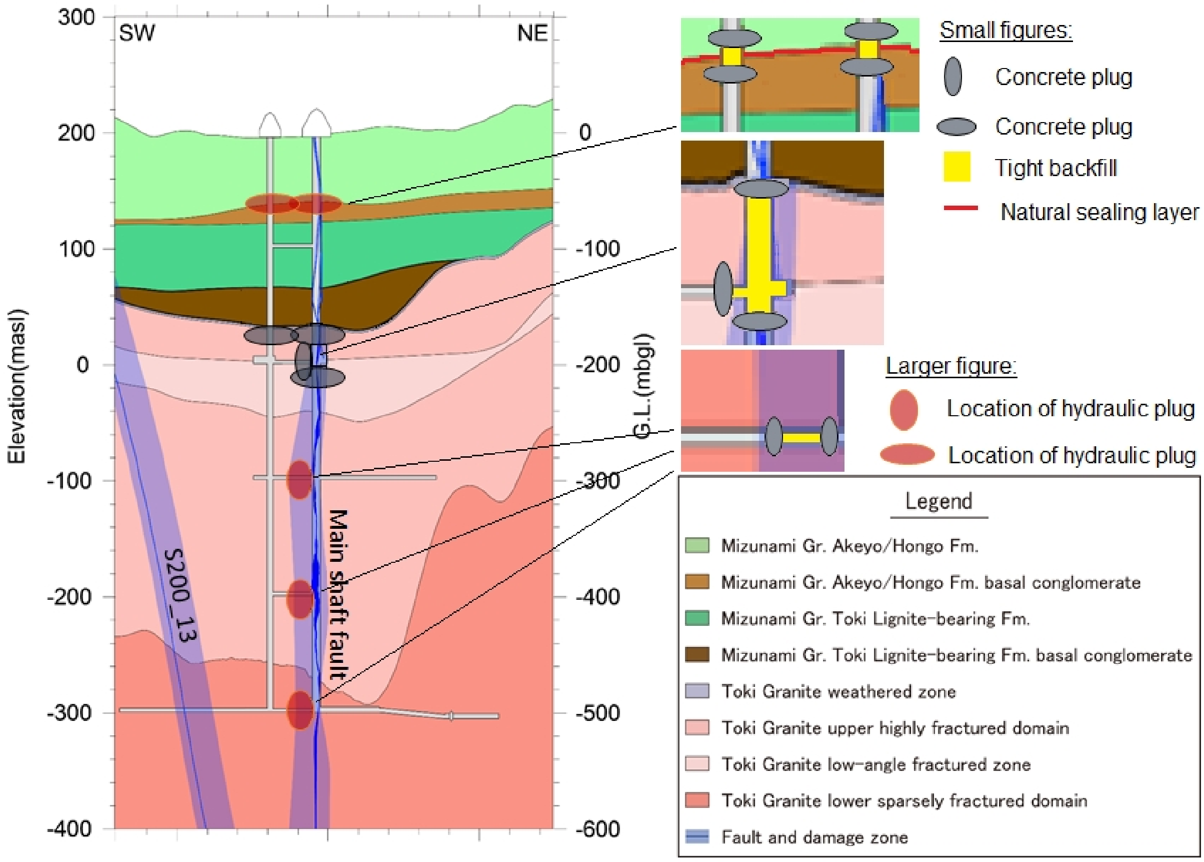


***Figure 40**. Mizunami URL closure design alternative B.*

3) Example for implementation of alternative A

An example of how design alternative A could be carried through is given in Figure 41 and Table 10. The table also includes a plug test that is described in section 5.6.1. The procedure (with plug test) has 33 phases. The design includes 12 (14 with plug test) concrete structures (plugs) of which four are in the two hydraulic plugs above the uranium bearing formation.

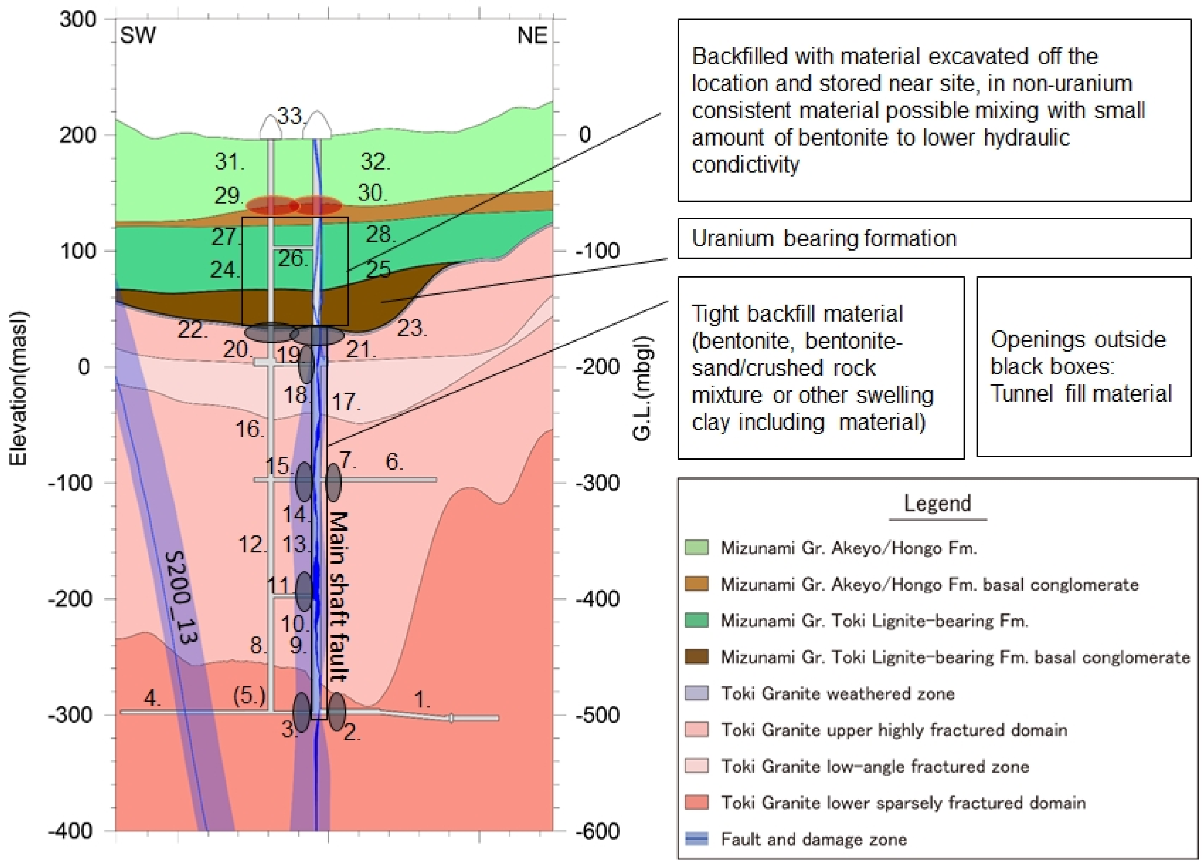


Figure 41. Mizunami URL closure design alternative A. Work steps also include plug test at gallery in the depth of -500 m (description in Section 5.6.1).

Table 10. An example of implementation work steps and their order for Mizunami URL closure design alternative A. Numbers refer to numbering in Figure 41.

Work step	Location	Closure component	Level (m from ground level)	Backfill material	Plug type
1	Gallery	Backfill	-500	Tunnel fill	-
2	Gallery	Plug	-500	-	Concrete structure
3	Gallery	Plug	-500	-	Concrete structure
4	Gallery	Backfill	-500	Tunnel fill	-
(5)	Gallery	Plug experiment (see Section 5.6.1)	-500	-	Two concrete structures with sealing structure in-between
6	Gallery	Backfill	-300	Tunnel fill	-
7	Gallery	Plug	-300	-	Concrete structure
8	Ventilation shaft	Backfill	-500 to -400	Tunnel fill	-

Work step	Location	Closure component	Level (m from ground level)	Backfill material	Plug type
9	Personnel shaft	Backfill	-500 to -400	Tight backfill material	-
10	Gallery	Plug	-400	-	Concrete structure
11	Gallery	Backfill	-400	Tunnel fill	-
12	Ventilation shaft	Backfill	-400	Tunnel fill	-
13	Personnel shaft	Backfill	-400 to -300	Tight backfill material	-
14	Gallery	Plug	-300	-	Concrete structure
15	Gallery	Backfill	-300	Tunnel fill	-
16	Ventilation shaft	Backfill	-300 to -200	Tunnel fill	-
17	Personnel shaft	Backfill	-300 to -200	Tight backfill material	-
18	Gallery	Plug	-200	-	Concrete structure
19	Gallery	Backfill	-200	Tunnel fill	-
20	Ventilation shaft	Backfill	-200 to -170	Tunnel fill	-
21	Personnel shaft	Backfill	-200 to -170	Tight backfill material	-
22	Ventilation shaft	Plug	-170	-	Concrete structure
23	Personnel shaft	Plug	-170	-	Concrete structure
24	Ventilation shaft	Backfill	-170 to -100	Excavated material returned to location	-
25	Personnel shaft	Backfill	-170 to -100	Excavated material returned to location	-
26	Gallery	Backfill	-100	Excavated material returned to location	-
27	Ventilation shaft	Backfill	-100 to -70	Excavated material/other rock material/ mixture including bentonite	-
28	Personnel shaft	Backfill	-100 to -70	Excavated material/other rock material/ mixture including bentonite	-
29	Ventilation shaft	Hydraulic plug	in cap rock	-	Two concrete structures with sealing structure in-between

Work step	Location	Closure component	Level (m from ground level)	Backfill material	Plug type
30	Personnel shaft	Hydraulic plug	in cap rock	-	Two concrete structures with sealing structure in-between
31	Ventilation shaft	Backfill	from cap rock to ground surface	Excavated material/other rock material/ mixture including bentonite	-
32	Personnel shaft	Backfill	from cap rock to ground surface	Excavated material/other rock material/ mixture including bentonite	-
33	Ground surface	Plug and/or landscaping	0	-	Concrete structure

4) Example for implementation of alternative B

An example of how design alternative B could be carried though is given in Figure 42 and Table 11. The table also includes a plug test that will is described in section 5.6.1. The procedure (with plug test) has 30 phases. The design includes 14 (16 with plug test) concrete structures (plugs) of which most are in the hydraulic plugs.

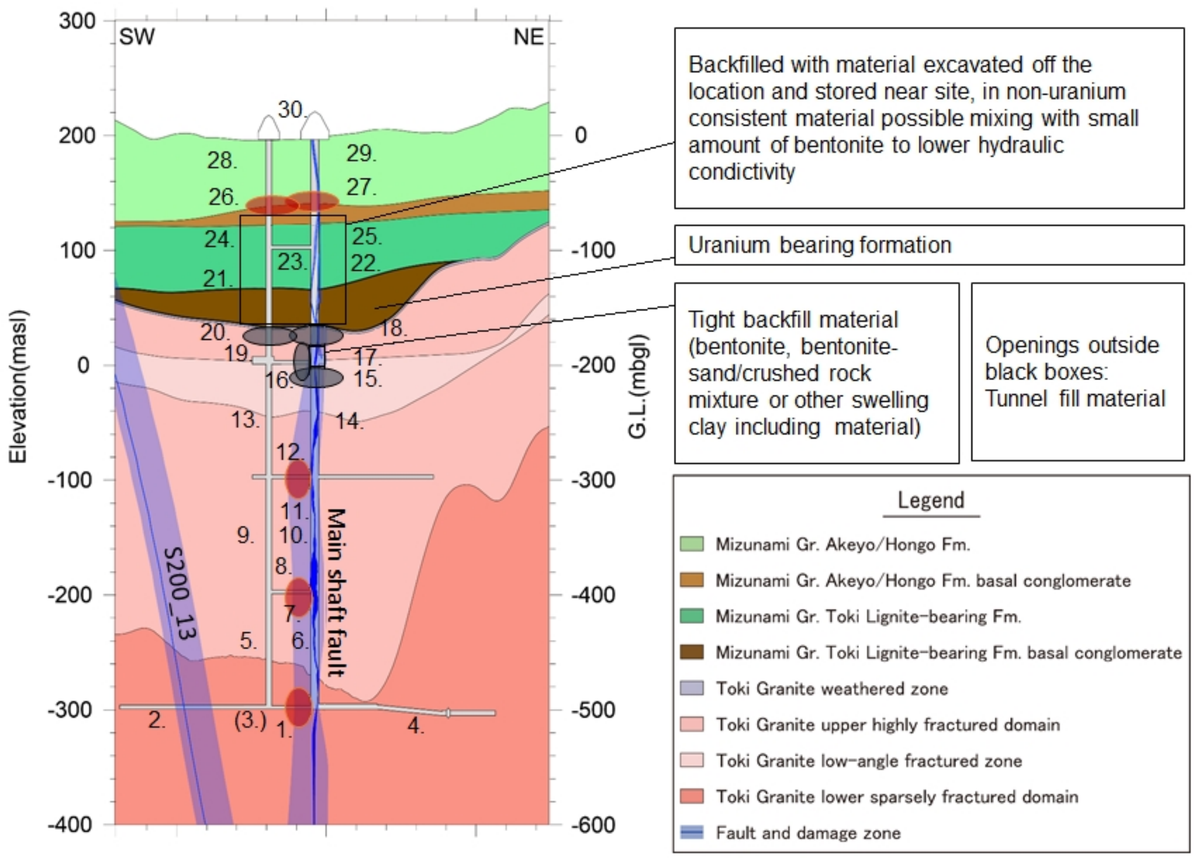


Figure 42. Mizunami URL closure design alternative B. Work steps also include plug test at gallery in the depth of -500 m (description in Section 5.6.1).

Table 11. *An example of implementation work steps and their order for Mizunami URL closure design alternative B. Numbers refer to numbering in Figure 42.*

Work step	Location	Closure component	Level (m from ground level	Backfill material	Plug type
1	Gallery	Plug	-500	-	Two concrete structures with sealing structure in-between
2	Gallery	Backfill	-500	Tunnel fill	-
(3)	Gallery	Plug experiment (see Section 5.6.1)	-500	-	Two concrete structures with sealing structure in-between
4	Gallery	Backfill	-500	Tunnel fill	-
5	Ventilation shaft	Backfill	-500 to -400	Tunnel fill	-
6	Personnel shaft	Backfill	-500 to -400	Tunnel fill	-
7	Gallery	Hydraulic plug	-400	-	Two concrete structures with sealing structure in-between
8	Gallery	Backfill	-400	Tunnel fill	-
9	Ventilation shaft	Backfill	-400 to -300	Tunnel fill	-
10	Personnel shaft	Backfill	-400 to -300	Tunnel fill	-
11	Gallery	Hydraulic plug	-300	-	Two concrete structures with sealing structure in-between
12	Gallery	Backfill	-300	Tunnel fill	-
13	Ventilation shaft	Backfill	-300 to -200	Tunnel fill	-
14	Personnel shaft	Backfill	-300 to -220	Tunnel fill	-
15	Personnel shaft	Plug	-220		Concrete structure
16	Gallery	Plug	-200		Concrete structure
17	Personnel shaft/gallery	Backfill	-200	Tight backfill	
18	Personnel shaft	Plug	-180	-	Concrete structure
19	Gallery & shaft	Backfill	-200 to -170	Tunnel fill	-
20	Ventilation shaft	Plug	-170	-	Concrete structure
21	Ventilation shaft	Backfill	-170 to -100	Excavated material returned to	-

Work step	Location	Closure component	Level (m from ground level	Backfill material	Plug type
				location	
22	Personnel shaft	Backfill	-170 to -100	Excavated material returned to location	-
23	Gallery	Backfill	-100	Excavated material returned to location	
24	Ventilation shaft	Backfill	-100 to -70	Excavated material returned to location	-
25	Personnel shaft	Backfill	-100 to -70	Excavated material returned to location	-
26	Ventilation shaft	Hydraulic plug	in cap rock	-	Two concrete structures with sealing structure in-between
27	Personnel shaft	Hydraulic plug	in cap rock	-	Two concrete structures with sealing structure in-between
28	Ventilation shaft	Backfill	from cap rock to ground surface	Excavated material/other rock material/ mixture including bentonite	-
29	Personnel shaft	Backfill	from cap rock to ground surface	Excavated material/other rock material/ mixture including bentonite	-
30	Ground surface	Plugs and/or landscaping	0	-	Concrete structures (or other)

5.4.4 Previous closure design and discussion

An alternative closure design was done before the current project and the design included shaft plugs in levels -50 m, -170 m, -300 m and -460 m. The design basis was the local geology and variations in it according to depth (Figure 43). The backfill material considerations done according to the previous design are presented in Table 12.

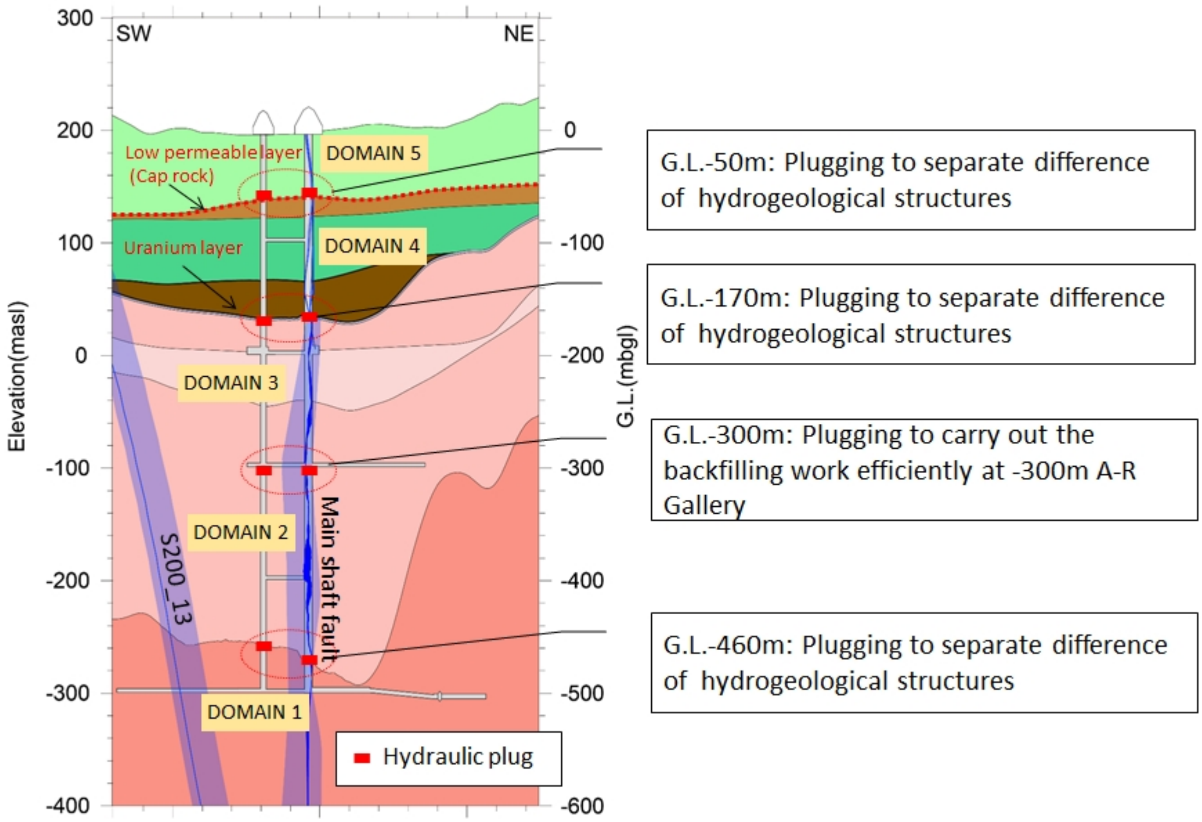


Figure 43*. Closure design done prior this project according to geological differencies according to depth.*

Concerning the top layer the designs are similar to the current project in that the sealing performance of the cap rock is significant and there is need to emplace a plug in that location to hinder potential waterflow through the shaft opening. The uranium layer is well isolated from the surface environment with this plug.

In the design proposed in this project it was concluded that the rock with relatively high hydraulic conductivities (Toki granite, upper highly fractured domain including low-angle fracture domain), is not isolated geologically from the uranium bearing formation (Mizunami Group, Toki lignite-bearing formation) and thus the shaft plug would not have a function in this location unless the shaft below is left only flooded or the backfill has hydraulic conductivities higher that the bedrock. If the backfill in shaft has high hydraulic conductivity, the requirements can determine a need to plug this location, but the sealing properties of this plug need not to be better that of the highly fractured rock, as the water (with potential leachates) would only pass the plug then in the contact of the two rock types (Figure 44).

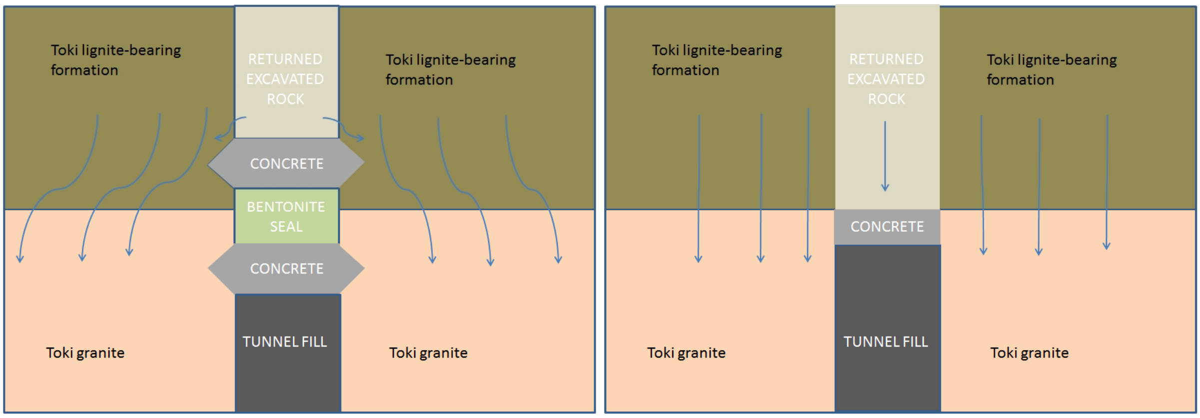


Figure 44. An illustration of how water with possible leachates will able to pass from one rock formation to another not depending on the built plug type. Reason for plug installation, without natural sealing barrier between rock types, is thus only to act as a firm base for returned excavated rock.

The level -300 m plugging in shafts is similar to the plugs discussed in this project that may need to be installed due to operational reasons. That is to facilitate backfilling. Plug in this location has no hydraulic performance, but allows time to be used for closure of tunnels at level -300 m. In this current project it was not clearly defined that these plugs would be necessary at this exact location, as the location depends much of the selected backfill materials.

The previous design places high importance to the transition between two Toki granite types at level -460 m. However, in viewing hydrogeological data there appears to be no clear difference between hydraulic conductivities of these two granites, though in larger model the other is sparsely and the other highly fractured. There is either no detectable change in hydrogeochemistry. This leads to conclusion that the contacts function as a barrier between two systems is not detectable and thus the plugs would have no sealing performance function in these locations. If further investigations bring change to these results a need for these plugs can be further considered.

In considering closure of the horizontal galleries at different levels, Table 12 presents the material options together with material option for shaft backfill.

Table 12. Backfill options presented in previous alternative closure design.

<table>
<tr><th>Domain</th><th>Depth</th><th>Geology</th><th>Gallery length</th><th>Backfill material (Case 1)</th><th>Backfill material (Case 2)</th><th>Backfill material (Case 3)</th><th>Work schedule (trial calculation based on 3m/day)</th></tr>
<tr><td rowspan="2">1</td><td rowspan="2">460 - 500m</td><td rowspan="2">Toki granite (Lower sparsely fractured domain)</td><td>Main Shaft side: 240m</td><td rowspan="6">Rock debris from Toki granite</td><td rowspan="6">Mixture of bentonite-sand-crushed rock. The mixed ratio is decided to permeability of the bedrock.</td><td rowspan="3">Shafts: Granitic rock debris</td><td rowspan="2">80 day</td></tr>
<tr><td>Vent. Shaft side: 162m</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">300 - 460m</td><td rowspan="2">Toki granite (Upper highly fractured domain)</td><td>Main Shaft side: 200m</td><td rowspan="2">67 day</td></tr>
<tr><td>Vent. Shaft side: 160m</td><td rowspan="3">Horizontal gallery: Mixture of bentonite-sand-crushed rock</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">170 - 300m</td><td rowspan="2">Toki granite (Upper highly fractured domain including low-angle fracture domain)</td><td>Main Shaft side: 320m</td><td rowspan="2">107 day</td></tr>
<tr><td>Vent. Shaft side: 150m</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">50 - 170m</td><td rowspan="2">Mizunami Group (Toki lignite-bearing formation)</td><td>Main Shaft side: 160m</td><td rowspan="2">Rock debris from Toki F.</td><td rowspan="2">Rock debris from Toki F.</td><td rowspan="2">Rock debris from Toki F.</td><td rowspan="2">53 day</td></tr>
<tr><td>Vent. Shaft side: 120m</td></tr>
<tr><td rowspan="2">5</td><td rowspan="2">0 - 50m</td><td rowspan="2">Mizunami Group (Akeyo/Hongo Formation)</td><td>Main Shaft side: 50m</td><td rowspan="2">Rock debris from Akeyo /Hongo F.</td><td rowspan="2">Mixture of bentonite-sand-crushed rock.</td><td rowspan="2">Rock debris from Akeyo /Hongo F.</td><td rowspan="2">17 day</td></tr>
<tr><td>Vent. Shaft side: 50m</td></tr>
</table>

In hydrogeological model of the site a difference was observed between different sides of the main shaft fault. This function of the main shaft fault, which is to act as a seal between two sides, was in the previous model returned to the similar-to-the-original state only with material alternative of mixture of bentonite-sand-crushed rock. If bentonite-sand-crushed rock is implemented to entire length of the gallery it has no hydraulic performance at the other end, where hydraulic properties of the bedrock are higher, and subjects the clay component to possible erosion.

5.4.5 Comparison of alternatives

Both alternatives A and B presented in this report fulfil the requirements. The previous design is challenging in that part of the materials are compatible with the requirements, but there is with this design excessive use of swelling material when less could be used and plug sites and their performance is not in all places in accordance with the requirements of returning the original bedrock properties. Comparison between the three alternatives is presented in Table 13.

Table 13. Comparison between closure design alternatives.

Variable	Alternative A	Alternative B	Previous alternative
Compliance with the requirements	Good	Good	Limited
Quantity of swelling material (in comparison to other alternatives)	High	Low	High
Number of concrete structures*	12	14	16
in galleries	4	7	-
in shafts	8	7	16
Number of hydraulic plugs	2	5	8
in galleries	-	3	8
in shafts	2	2	-

*two in each hydraulic plug and one in each marked in illustrations as single concrete structures. Possible test plugs are not included in numbers.

If design is based on alternatives compliance with the requirements, based on the strategy presented in this report, only alternatives A and B comply. Alternative A complies directly with the requirement of returning bedrock properties as similar to the original ones as the hydraulic conductivity of main shafts backfill can be designed to match the ones of the main shaft fault. Alternative B on the other hand returns the sealing performance of the main shaft fault, thus returning the bedrock properties in both sides of the main shaft fault.

Of the two alternatives alternative A has more swelling material but less concrete structures, resulting potentially in quicker installation but material costs of bentonite could rise to some level (depending on the final selected materials). Alternative B minimizes the use of swelling material to the sealing cores of hydraulic plugs and to the short shaft section approximately at the depth of -200 m (the "three dimensional hydraulic plug"). The quantity of concrete structures is higher in alternate B and in thinking that it takes time to construct these plugs the implementation of this type of closure design could possibly take longer than that of alternative A. The material costs would be lower due to lesser volume of swelling material, depending of course on the selected material, but work time may finally level the costs of these two designs.

In selection of design alternatives the consideration of exact material selection has an important role in cost estimation. If hydraulic plugs utilise dense bentonite blocks it should be affirmed where they can be compressed and that the transportation can be done with required quality needs to result in high quality end result. The use of mixture materials prepared on or near site and installed in situ could lower the costs. However, it may be in interest of international organizations to test installation of certain material and installation method, and for this reason materials should not be set too early in the project.

5.5 Site scale monitoring and modelling

5.5.1 Monitoring

In order to obtain detailed enough information from a full scale closure, monitoring is needed. Both evolution of the closure components (e.g. swelling pressure) and the site should be monitored in such detail that predictive modelling can be undertaken and compared to the monitoring results.

Site property monitoring should include at least monitoring of groundwater chemistry, hydrogeological response and seismic monitoring of the site.

Monitoring of the groundwater composition and hydrogeology should be continued during the operation, including a review of parameters (and measurement/sampling locations), so that post-closure monitoring results can be compared to baseline data and data obtained during operational phase (this means that at least the current monitoring locations need to be included during the closure and post-closure monitoring periods). The focus of relevant parameters could include at least:

- salinity development,
- alkaline leachate monitoring,
- colloid monitoring from backfill materials, and
- hydrogeological response (e.g. inflows, hydraulic head development, hydraulic pressures).

At MIU ongoing seismic monitoring should be continues and potentially the current grid updated. Also, surficial GPS monitoring is recommended. Monitoring of the rock stress development can be also considered.

The performance of closure materials should include monitoring of the saturation of the backfill and development of the swelling pressures at least in selected locations where swelling components are included.

Monitoring of the backfill material performance can be also done locally as a part of localized experimental set ups. The configurations of these would greatly depend on the final experimental plan and objectives set by the project participants.

In case of installation of plugs, their performance can be monitored especially in relation to the leakage through the plugs and hydraulic pressures against the plugs.

5.5.2 Modelling

It is recommended that predictive modelling should be included in the research plan. The predictive modelling can include prediction of the development of the site properties and properties of the closure components themselves, e.g.:

- saturation of the backfill
- swelling pressure of the backfill
- pressure against the plug
- leakage through the plugs
- rock stress redistribution
- changes in the flow pattern of the site
- inflows to the facilities
- changes in the water table
- changes in the groundwater chemistry

The monitoring results can be used to calibrate the models.

5.6 Experiments

Several experiments can be conducted during the closure process in addition to the monitoring described above. These can be divided to technical and scientific experiments, but in reality these overlap and both produce results for other, too. Potential experiments include:

- Scientific experiments:
  - Backfill performance (and colloid monitoring)
  - Non-swelling clay test for sealing purposes (e.g. illite)
  - Concrete performance experiment
- Technical experiments:
  - Installation, QA.
  - Monitoring experiments
  - Removal of foreign materials (i.e. shotcrete)
  - Borehole sealing

5.6.1 Backfill erosion experiment

A high conductivity fracture/zone S200_13_2 locates at the gallery at the depth of -500 m. On contrast to was thought according modelling that was done before excavation of MIU at that depth the S200_13 does not appear to divide the region to two bedrock areas with differing characteristics and measurements do not indicate that S200_13_2 would have any such function either. On both sides the hydraulic conductivities are similar and there is no apparent difference in geochemistry. This gives an opportunity to use this very conductive feature for test purposes.

In this report a bentonite erosion experiment is suggested for this location (Figure 45). The experiment would be a building of a hydraulic plug at the location, leaving the dense, highly compacted bentonite at the fracture location. By then observing the swelling pressure of bentonite within the hydraulic plug the results could give results on both saturation and erosion as the pressure could at first rise but then fall as bentonite is flushed away. If behaviour is unexpected the measurements could give valuable information on material behaviour at real conditions at real size tunnel conditions. Monitoring of the saturation would allow also observation of potential uneven saturation and spatial differences in development of bentonite properties.

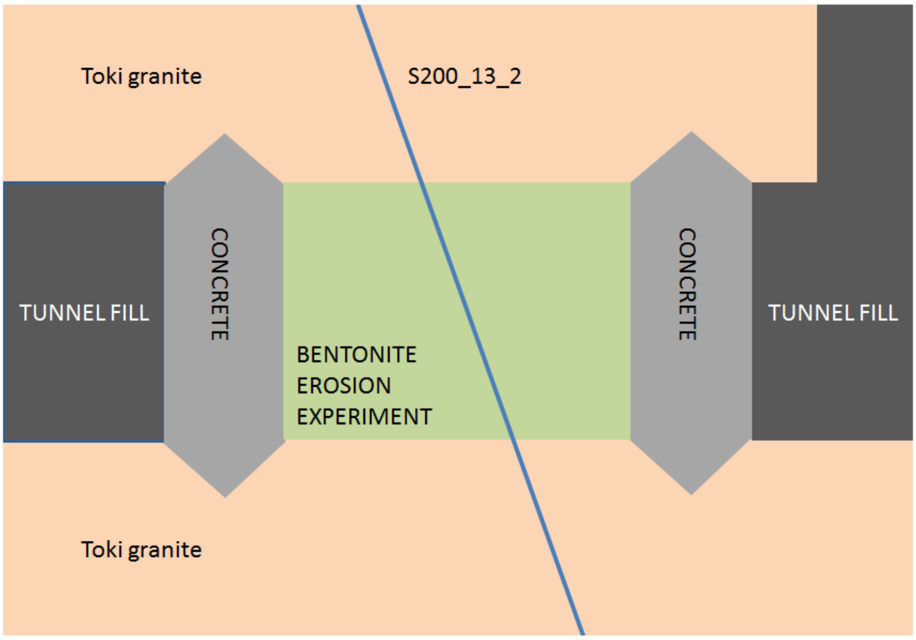


Figure 45. Backfill erosion experiment at level -500 m gallery at the location of S200_13_2.

A few difficulties would persist at the setup of the experiment, not least erosion of material during building phase. These challenges can be gotten around with good planning and possibly installation of backfill through a man hole rather than placing it before installation of the second concrete structure. High income of water will need draining off while the concrete sets, but all challenges due to inflow are possible to be overcome. The location is very close to the ventilation shaft and this will need further consideration on how that side of the experiment can be plugged (that is there enough space to build a stabile concrete structure with required performance capability).

Should the experiment be implementable the monitoring can for a while be conducted at level -500 m and as the closure advances the monitoring can be continued at higher level/ground level, if there is more left to monitor. This depends on the behaviour of the materials (erosion speed) and results of the monitoring.

Erosion of bentonite, both mechanical and chemical, is a topic that has relevance in the repository safety assessments. In addition to large scale monitoring of colloids in the groundwater and the backfill test suggested above, also smaller scale tests could be planned for the MIU closure. This topic could be included in the borehole sealing test.

5.6.2 Non-swelling clay test for sealing purposes (illite)

Since the erosion of bentonite and potential process of illitisation are of concern in some repository designs, there would be interest in studying performance of other clay materials. At minimum, this could include installation test of selected alternative non-swelling materials. Also other clay materials could be tested.

5.6.3 Concrete performance experiment

There is a substantial quantity of concrete in Mizunami URL used for support and for grouting. Both shafts are lined with thick concrete, with minimum thickness of 40 cm. The concrete cannot be removed from the shafts, as it would destabilise the shafts and inflow rates would be uncontrollable. Leaving the concrete in URL does not affect the behaviour of the closure, for it has no long-term requirements and monitoring time would be limited. With the expected lifespan of concrete, the remaining concrete would not form pathways for groundwater and mitigate the sealing systems. With design, the critical points are cut through the concrete with hydraulic plugs and the system behaviour should remain at required level.

The concrete lining in shafts could be used as an experiment material. The concrete mix is known and it has design properties and an expected lifespan for duration. After closure the concrete remains in deep groundwater conditions and is subjected to changes in these conditions. It could be possible to return to site after a certain time (e.g. 5-20 years after closure) and core drill a sample of the concrete from depths, at the location of the shafts concrete lining. After core drilling the hole could again be filled with concrete. Potential test idea is illustrated in Figure 46.

The challenges with this are:

1. The difficulty of drilling at a very narrow concrete layer.
2. Following the closure design will mean cutting the concrete lining at least in two locations (hydraulic plug at approximately -50 m depth).

3. Contacts with rock would also be of interest, which poses even more difficulties for drilling positioning.

A decision of this experiment is not necessary to be done quickly as the concrete will need time to endure any potential changes.

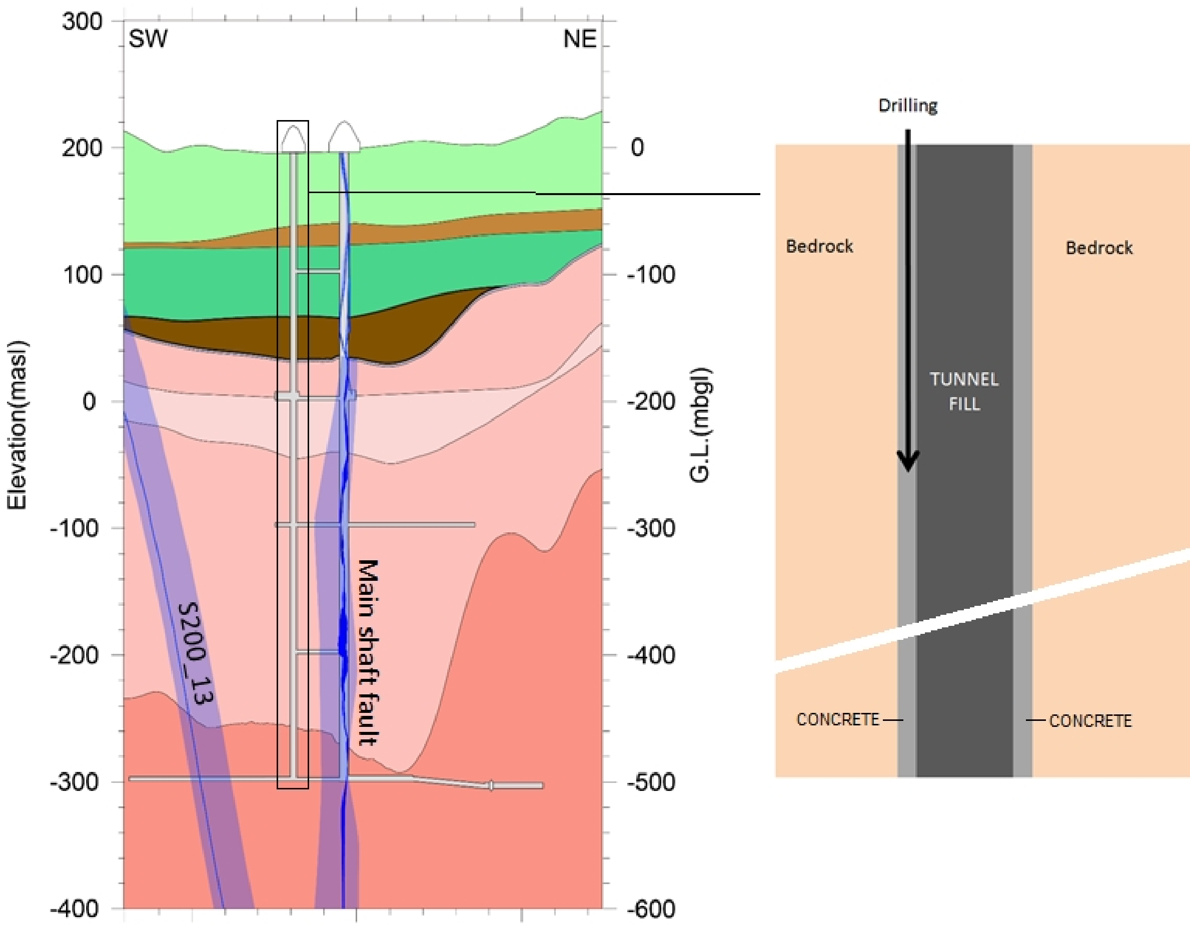


Figure 46. An illustration of potential concrete experiment to view deterioration of concrete after. Concrete can be core drilled from shaft wall lining.

5.6.4 Installation, initial state and QA

Backfill material installation is a state of the art process in big scale. It will require special vehicles and specific designs for each individual detail. With MIU closure, what would be needed are material acquisition, transport and storing, potential local manufacturing at site, transfer to underground and installation/building. With all steps quality control will need to follow the procedure and all will need to be recorded. The closure installation is extremely important in considering the future repository and its closure. The implementation will bring out aspects that can be considered already when the future repository will be designed.

Testing and demonstrating the quality control and quality assurance of the implementation requires that:

- clear requirements are set for the initial state and for the materials used, and
- that adequate procedures will be developed for verification of the initial state of the closure.

This would include studies assessing adequate quality control of materials as received, testing of their relevant properties when pre-fabricated and development of non-destructive methods to verify the initial state. These methods are widely used in relation to waste containers, and should be sought for also clay, cement and rock based materials. The advantage of various types of non-destructive methods is also that they are usually done by using various spectral methods that do not need long analysis times in laboratories and can be effectively analysed with dedicated soft-wares. Within a closure experiments, also methods that will work also in industrial scale could be developed.

5.6.5 Monitoring experiments

Monitoring is part of the project at MIU. As discussion is raised about monitoring after closure in countries planning repositories for HLW, there is potentially international interest to test new developed monitoring methods in realistic environments, for which MIU offers a great possibility. There is little data on on-going investigations concerning monitoring methods under development, but as MIU closure project is taken forward it is an excellent chance to engage scientific community in this discussion and find potential test projects.

5.6.6 Removal of foreign materials

Limitation of foreign material introduction into repository volumes is done during construction and operation phases, but before closure many components necessary during operation will be removed. Such components are for example HVAC systems, draining system and concrete structures. Other removals are quite simple in comparison to the removal of shotcrete. Removal of shotcrete is here discussed in more detail, because it is important in actual repositories in future. Because MIU does not hold radioactive waste, removal of shotcrete is only discussed from the aspect of restoration of hydraulic conditions of the site.

In closure design most emphasis is given for restoration of bedrocks natural hydraulic characteristics. This is what closure, and especially backfilling in closure, aims at. To gain good contact with bedrock, the shotcrete and other structures following the tunnel wall will need to be removed or at least intersected for a sufficient length. If shotcrete is not removed, it can degrade with time and has potential to form a flow path along the tunnel, between backfill and bedrock, together with already slightly weakened EDZ in rock wall behind it. With removal of shotcrete, the sealing can be produced with required performance.

Shotcrete removal is not routinely done anywhere. There are experimental means to do it and methods can be further developed. It is a fairly difficult operation, in large part due to occupational safety reasons. When shotcrete support is removed the safety of the workers will need to be guaranteed. This is an aspect only little investigated and hardly nothing is published about this.

It is clear that shotcrete will not be removed from MIU facility, but demonstration of the removal practices could be included in the experiments. In Mizunami URL the concrete will not harm the performance of closure as the monitoring time of the closed URL is short in comparison to how long the repository closure components need to retain their performance. In fact the remaining of concrete is very good for investigation purposes to inspect the deterioration of concrete. Whether it has effect on bentonite materials can potentially be monitored with time from ground surface. In long term the degradation products of the left concrete will be sufficient to fill the MIU facility openings. In MIU there is no long-term safety aspect in considering potentially forming narrow flowpaths along tunnel walls (within 100 years or more), as there are no radioactive materials in MIU.

5.6.7 Borehole sealing experiment

Due to requirement in radioactive waste repositories (for HLW) to close routes from disposal level to ground surface, also deep investigation holes will need to be closed if they pose potential to act as such routes. The effect of boreholes for the local hydrogeological characteristics can be examined with modelling and the requirements for closure performance may vary between different sites according to the characteristics and borehole sizes, depths, and bedrock features they intersect. In future repositories there will also be long boreholes underground made for other purposes, for example as pilot holes for potential deposition tunnel sites, which are then left as they were cored if characterisation revealed that a deposition tunnel should not be excavated at that location. All possible long holes, which intersect different hydraulically transmissive areas, will potentially need to be closed to restore hydraulic bedrock properties and so the boreholes will not act as shortcuts for groundwater.

There are several investigation boreholes in MIU (Figure 47) and in some of them instrumentation may be carried on after closure for a limited time but because part of them would not be used it could be possible to test an installation method in one of these holes. Reasoning for using MIU rather than a random location in e.g. mining surroundings, is the monitoring and characterisation of MIU site. In part of the holes it could be possible to install monitoring in test materials and read the results from adjacent tunnel (for example boreholes cored from -200 m level downwards could potentially be monitored from shafts). Within the test the materials selected at later stage can be tested and after installation, if this is done at an early phase, it is possible to recover the materials. As the time materials would be at place would remain short (due to MIU closure schedule) it might be beneficial to leave the materials and use this as an installation test only for future repository closure purposes. However, if potential boreholes are all needed for monitoring after closure, borehole closure experiment is not feasible.

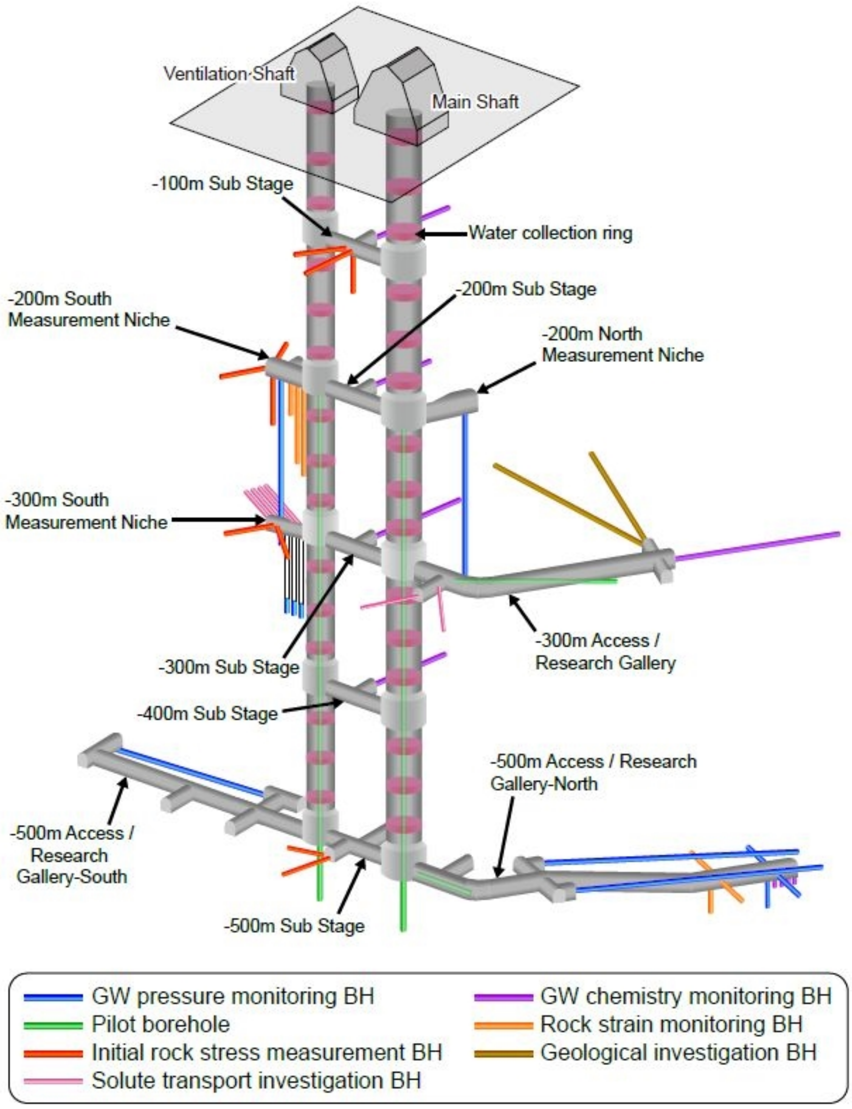


Figure 47. *Underground boreholes at Mizunami URL, underground.*

5.7 Technical challenges

Closure of the entire URL is a big task that will need detailed planning as not only on what materials and structures will be used where, but from the actual implementation point. The biggest challenges arise from the seepage water, as the MIU inflow rates are fairly high, and the dismantling of structures together with installation of closure components. For this reason there may be need for temporary shields or additional plug structures. Water flow into tunnels and shafts during installation work will need to be constrained/pumped out without it harming the installed materials so the performance would not be jeopardised.

In an attempt to demonstrate or test an actual repository closure, this would require the removal of shotcrete and other structures that follow tunnel and shaft walls and could with time form a hydraulic channel from one section to another. It is clear that in Mizunami URL this cannot be carried through extensively. Discussion of this topic is in Section 5.6.7.

5.8 Schedule constraints

Within the given timeframe, time needs to be allocated for:

- Overall planning
- Detailed design of the closure and monitoring
- Implementation (construction and installations)

It is advised that monitoring would continue after the closure of the facility. The duration depends on the objectives set for the closure as a whole as well as individual experiments. It may also depend on the functionality of e.g. wireless monitoring systems and access to observation boreholes. It would be recommended that at least 10 year period would follow the closure regarding groundwater system monitoring. It would be good to follow the development until saturation of the system and then at least until the followed parameters reach steady state or state that can be considered to represent natural variation.

The overall scheme for the closing project is presented in Figure 48. This scheme accounts for:

- The ongoing experiments during the 2015-2019 period.
  - The experiments at the -500 m level galleries will be ongoing until 2019, but it should be considered if the backfilling of other locations could be started already before 2019.
- Planned backfilling experiments (can be modified and implemented in the revised detailed design, depending on the objectives set for the closing process).
- Monitoring of the site is ongoing and should be included in the monitoring plan development, but essentially monitoring that is ongoing now should continue throughout the time 2015-2022 (January).
  - Current monitoring programme should be revised at early stage of the project in order to ascertain sufficient collection of pre-closure data from groundwater sampling.
- It should be cleared how long monitoring actions can be undertaken at MIU site regarding the land-use and other plans that the local municipality may have. It is recommended that post-closure monitoring will be implemented for both:
  - site monitoring, and,
  - closure system monitoring.

This if of importance in order:

- to obtain relevant scientific information (interest of the RWM community), and,
- to monitor environmental impact (mainly in relation to groundwater quality) (interest of the local community).

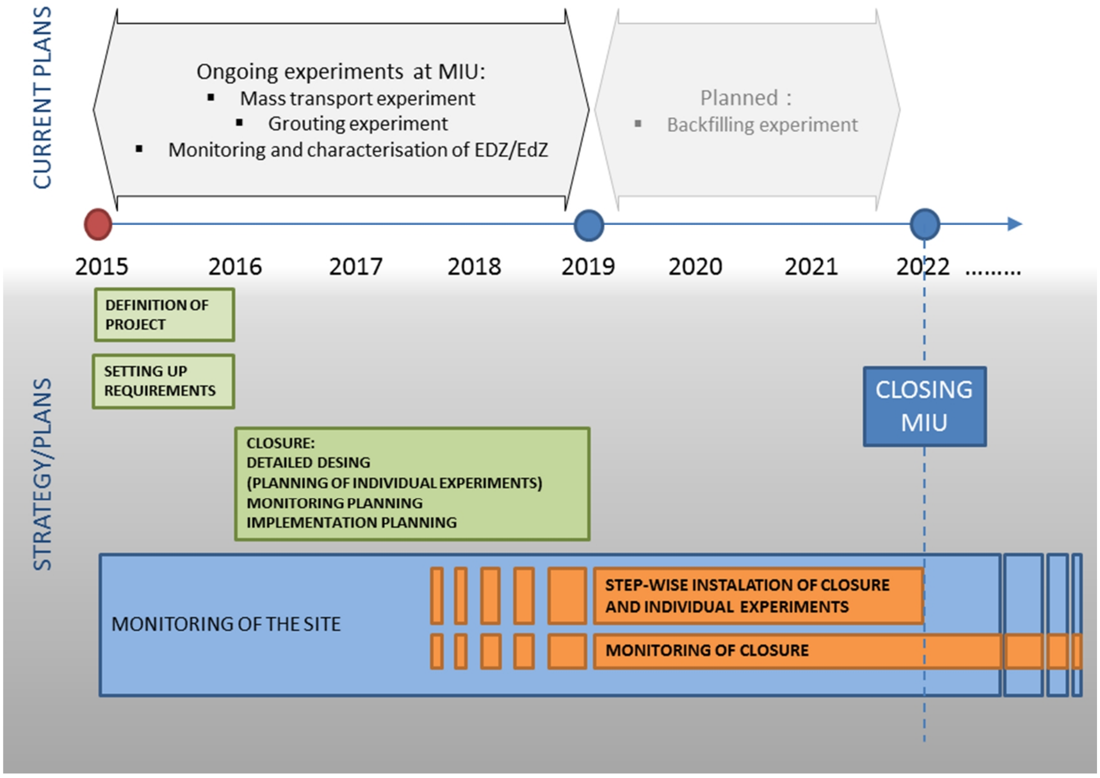


Figure 48. Overall schedule of closing MIU

Implementation of any closure plan that involves backfilling of the underground spaces is dependent on the volumes to be filled and the capacity of the equipment.

The volumes of the MIU are listed in Chapter 2. For rough example of backfilling tunnels with crushed rock following approximation has been made:

Assuming 16 hours per day (2 shifts) with 10t capacity with shaft, daily production would be around 65t. This applies for galleries. Shaft backfilling can be faster, around 6 times faster than gallery backfilling.

For special experiments regarding closure structures, such as backfilling and plugging tests, time for installation is needed to be reserved. It is approximated that about 1 month would be suitable time for single concrete plug installation, however this also depends on the detailed structures in the plug.

In order to implement the full closure the schedule has been analysed. Sufficient time needs to be allocated to closure design, implementation planning and the actual implementation. Implementation of the backfilling types with special density requirements and plugging takes more time in this option as the detailed monitoring systems also to monitor backfill behaviour need to be installed and tested. However, the gallery backfilling could be started already during the period 2015-2019. Schematic schedule is presented in Table 14.

The monitoring systems should be such that after initial monitoring from short distance (e.g. -500 m gallery backfills), also monitoring systems that would allow monitoring of the closure material behaviour (esp. swelling and settling) should be placed, with target monitoring period, at least until 2022, and even longer if possible from the political point of view.

Table 14. Preliminary schedule regarding design/planning and implementation.

Step (year)	1	2	3	4	5	6	7	8
JAEA planning and definition of the project								
Seeking collaboration internationally								
WORK SHOP								
Setting up requirements for the closure								
Detailed closure design								
Closure monitoring planning (esp. review on geochemical parameters)								
Closure implementation plan								
Step-wise installation of closure								
Planning of short term experiments								
Short term experiments								
Potential monitoring of the experiments								*
Monitoring of the site								*

*should be continued also after closing the MIU.

6 Summary

The strategy for closing MIU is to produce full backfilling of the underground spaces, which provides permanent and safe solution for closing the URL and returning the land to the local municipality. The overall flow of the developing the strategy into a plan is presented in Figure 49.

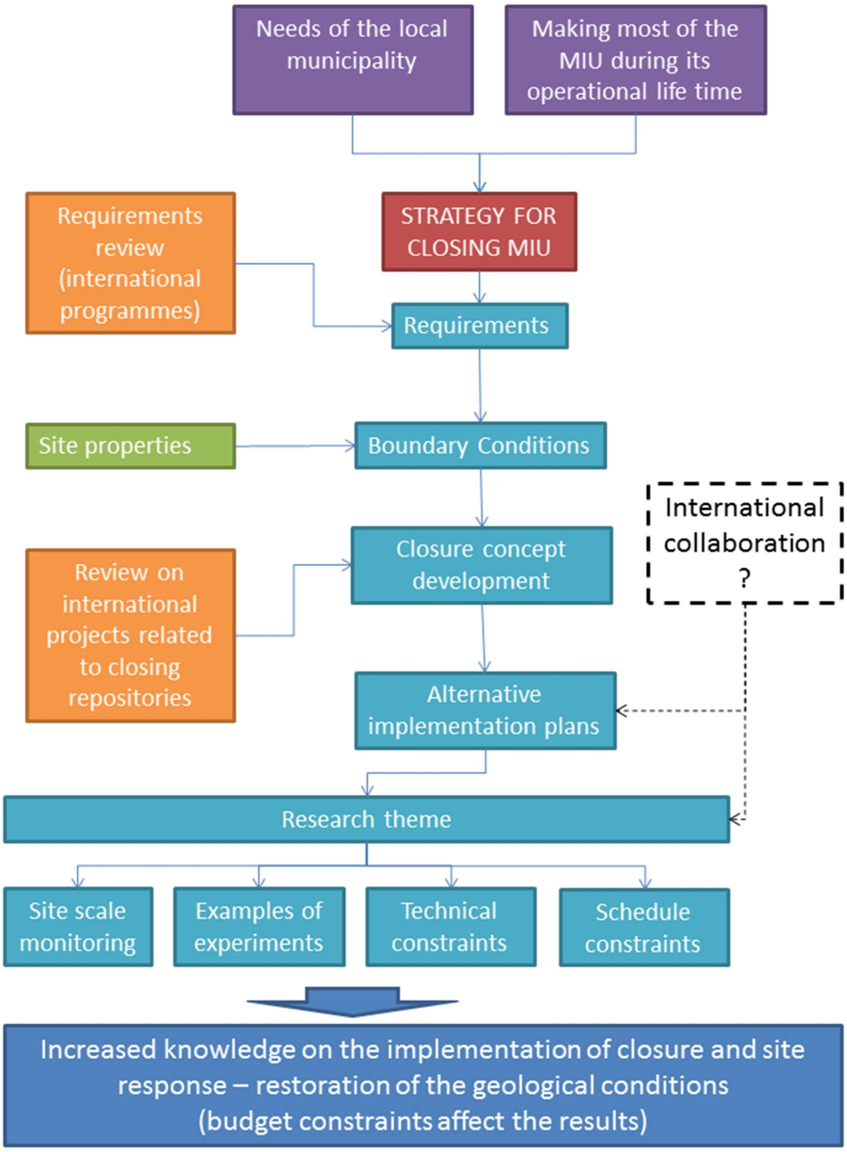


Figure 49. Overview of the strategy and implementation plan development.

The strategy proposed in this report is designed to contribute to overall project goals set for MIU; those focussing on establishing techniques for investigation, analysis and assessment of the deep geological environment and developing engineering solutions for underground repositories. The greatest potential in MIU closure lies within testing and demonstrating full-scale system. This has not been done anywhere in the world yet in relation to radioactive waste disposal. Full-scale closure enables gaining experience on operational and post-closure implementation and monitoring of the full-scale system. Furthermore, it aims at providing data that can be used to develop modelling of the site behaviour. This topic of site restoration is a theme in geoscientific research that has been very little studies by full scale experiments to date. The development presented in this report is based on the site characteristics of the MIU site and the information available from the scientific literature (Figure 50).

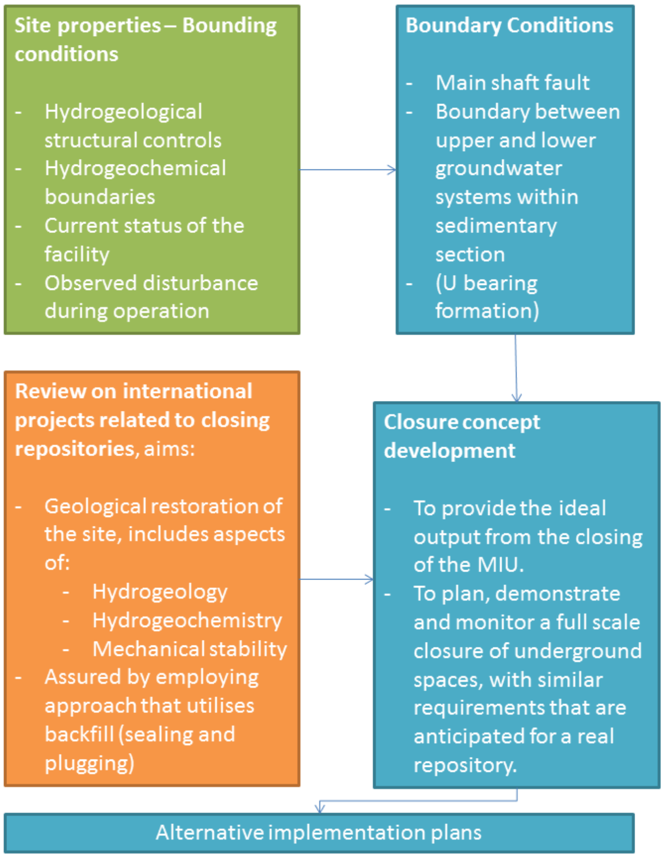


Figure 50. Derivation of boundary conditions and development of closure concept.

The strategy is planned focussing on scientifically optimal solution, and thus some practical constraints regarding budget and detailed schedules are not discussed in detail. The strategy is based on the idea of full backfilling and closing of the facility. Due to the full scale nature of the plan, international collaboration is seen as of great importance in order to be able to use the full potential of the MIU facility, before the end of operation.

Due to schedules foreseen at the moment for MIU, it is clear that retrieval experiments are not feasible. Large scale experiments with retrieval take longer time than what is available at MIU. This is reflected in the plan by focussing on step wise backfilling, including experiments that can be monitored during the operational period and by including long-term monitoring from the surface.

In addition to experience on design, installation and monitoring also QA for backfilling should be developed during the project, in order to verify the initial state of the closure.

The properties of MIU site, such as high inflow rates, extensive shotcreting etc. that would be considered problematic for an actual disposal facility are useful considering closure demonstration. Especially the inflow would allow quicker saturation of the installed materials, and the extensive use of cement could be monitored and used as a benchmark for OPC (Ordinary Portland Cement) systems.

Also, galleries located at higher levels would provide information that would be useful also L/ILW repositories. In addition, sedimentary cap rock on top of Toki granite has been taken into account in the design, providing relevant information of closing sedimentary site repositories. This might be a key also for gaining interest from organisations that are currently focussing on sedimentary host rocks/ shallow disposal.

Since the full scale demonstration of closure would be internationally ambitious project, the overall theme should be such that it supports disposal programmes in general. The main objective is to cover the gap in demonstrating closure:

- testing and development of the repository closure implementation and monitoring applied to both crystalline and sedimentary environments providing relevant information on closure structures to be used at the whole depth range of the geological disposal.

In addition, the theme can be subdivided by disciplines that include:

- design and implementation,
- quality control and quality assurance,
- monitoring,
- demonstrating long-term safety aspects of closure designs, and,
- modelling.

Although MIU closure does not need to perform in the long-term as a real repository would, it is still a topic that is accounted for in order to design closure demonstration that would serve the radioactive disposal research. The extensiveness of these considerations depend in the end of the final experimental set ups and objectives that will be set on them. Closure is part of the repository systems in all advanced high level waste disposal programmes. Posiva and SKB have assessed closure performance as a part of their long term safety assessments (see e.g. Posiva 2013, SKB 2011) and this is likely to be the case in all national programmes worldwide. MIU closure could provide very valuable information for the Japanese radioactive waste disposal programmes as well as internationally.

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国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 組立単位	
	名称	記号
面積	平方メートル	m^2
体積	立方メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度[(a)]，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立方メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率[(b)]	（数字の） 1	1
比透磁率[(b)]	（数字の） 1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン[(b)]	rad	1 [(b)]	m/m
立体角	ステラジアン[(b)]	sr[(c)]	1 [(b)]	m^2/m^2
周波数	ヘルツ[(d)]	Hz		s^{-1}
力	ニュートン	N		$m\ kg\ s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度[(e)]	℃		K
光束	ルーメン	lm	cd sr[(c)]	cd
照度	ルクス	lx	lm/m^2	$m^{-2}\ cd$
放射性核種の放射能[(f)]	ベクレル[(d)]	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト[(g)]	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		$s^{-1}\ mol$

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	$m^{-3}\ s\ A$
表面電荷	クーロン毎平方メートル	C/m^2	$m^{-2}\ s\ A$
電束密度，電気変位	クーロン毎平方メートル	C/m^2	$m^{-2}\ s\ A$
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1}\ s\ A$
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}\ mol$

表５．SI 接頭語

乗数	名称	記号	乗数	名称	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60 s
時	h	1 h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10 800) rad
秒	”	1”=(1/60)’=(π/648 000) rad
ヘクタール	ha	$1\ ha=1\ hm^2=10^4 m^2$
リットル	L，l	$1\ L=1\ l=1\ dm^3=10^3 cm^3=10^{-3} m^3$
トン	t	$1\ t=10^3\ kg$

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	$1\ eV=1.602\ 176\ 53(14)\times 10^{-19} J$
ダルトン	Da	$1\ Da=1.660\ 538\ 86(28)\times 10^{-27} kg$
統一原子質量単位	u	1 u=1 Da
天文単位	ua	$1\ ua=1.495\ 978\ 706\ 91(6)\times 10^{11} m$

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	$1\ bar=0.1 MPa=100\ kPa=10^5 Pa$
水銀柱ミリメートル	mmHg	1 mmHg≈133.322Pa
オングストローム	Å	$1\ Å=0.1 nm=100 pm=10^{-10} m$
海里	M	1 M=1852m
バーン	b	$1\ b=100 fm^2=(10^{-12} cm)^2=10^{-28} m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デシベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	$1\ erg=10^{-7}\ J$
ダイン	dyn	$1\ dyn=10^{-5} N$
ポアズ	P	$1\ P=1\ dyn\ s\ cm^{-2}=0.1 Pa\ s$
ストークス	St	$1\ St=1 cm^2\ s^{-1}=10^{-4} m^2\ s^{-1}$
スチルブ	sb	$1\ sb=1 cd\ cm^{-2}=10^4 cd\ m^{-2}$
フォト	ph	$1\ ph=1 cd\ sr\ cm^{-2}=10^4 lx$
ガル	Gal	$1\ Gal=1 cm\ s^{-2}=10^{-2} ms^{-2}$
マクスウエル	Mx	$1\ Mx=1 G\ cm^2=10^{-8} Wb$
ガウス	G	$1\ G=1 Mx\ cm^{-2}=10^{-4} T$
エルステッド[(a)]	Oe	$1\ Oe \triangleq (10^3/4\pi) A\ m^{-1}$

(a) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	$1\ Ci=3.7\times 10^{10} Bq$
レントゲン	R	$1\ R=2.58\times 10^{-4} C/kg$
ラド	rad	$1\ rad=1 cGy=10^{-2} Gy$
レム	rem	$1\ rem=1\ cSv=10^{-2} Sv$
ガンマ	γ	$1\ \gamma=1\ nT=10^{-9} T$
フェルミ		1 フェルミ=1 fm=10^{-15}m
メートル系カラット		1 メートル系カラット= 0.2 g = 2×10^{-4}kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1 cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー），4.184J（「熱化学」カロリー）
ミクロン	µ	$1\ \mu=1 \mu m=10^{-6} m$

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