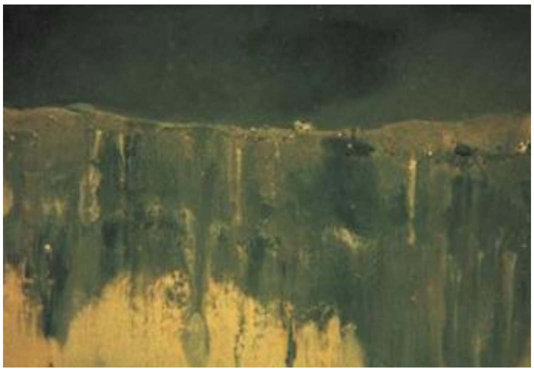
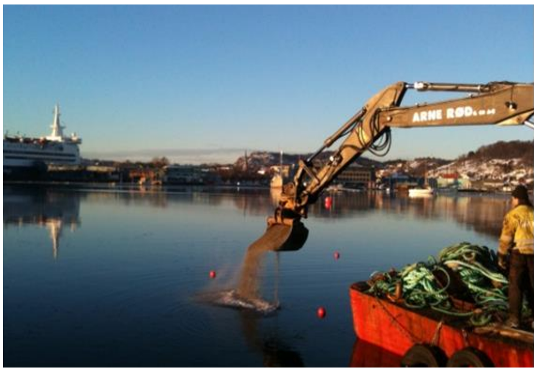
Swedish Geotechnical Institute

In-situ capping of contaminated sediments

Overall summary

Joseph Jersak, Gunnel Göransson, Yvonne Ohlsson, Lennart Larsson, Peter Flyhammar, Per Lindh

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Preface

Contaminated sediments occur to some extent in almost all countries, both in fresh waters and marine environments. Sediment contamination in most countries results from historical releases, when regulatory controls were lacking or minimal, although releases occur to some extent also today. Therefore, the problem of contaminated sediments and risks they can pose to the environment and humans is not unique to Sweden.

Globally-accepted technologies for sediment remediation generally rely on either removing the contaminated sediment then managing it *ex-situ*, or remediating sediment contamination in-place, *in-situ*. *In-situ* capping is an internationally recognized and accepted technology for remediating contaminated sediments. The technique is well established in other countries like the USA, Norway and Canada, in contrast to Sweden, where capping has been very limited to-date.

The Swedish Geotechnical Institute (SGI) has the national responsibility for research, technological development and knowledge building for remediation and restoration of contaminated sites. The aim is to raise the level of knowledge and increase the rate of remediation action, in order for Sweden to achieve the national environmental quality objectives. As part of this, knowledge should be mediated to others, such as regulators, consultants, laboratories, problem owners, contractors, etc. by (among other things) issuing publications.

This publication is intended to serve as a basis for the design and assessment of remediation alternatives to dredging. The publication aims to provide a technology overview of various capping-based techniques and to describe possibilities and limitations. The overall aim is to establish a basis for capping as a viable *in-situ* remediation alternative for managing contaminated sediments.

This publication includes a state-of-the-art review of the remedial practices of *in-situ* capping of contaminated sediments. The publication comprises a main text plus several supporting, but stand-alone, appendices. These supporting appendices include: a preliminary review of contaminated sediments in Sweden; a general overview of established *ex-situ* and *in-situ* sediment remediation technologies; a preliminary overview of remedial sediment capping projects worldwide; a short discussion on anticipated challenges with capping Sweden's fiberbank sediments; and an extensive, up-to-date collection of relevant technical and other international references.

The publication is a result of a co-operation between the Swedish Geotechnical Institute (SGI) and SAO Environmental Consulting AB (SAO). The main author is Dr. Joseph Jersak (SAO).) and co-authors are Gunnel Göransson, Yvonne Ohlsson, Lennart Larsson, Peter Flyhammar and Per Lindh at SGI. Professor Danny D. Reible, Texas Tech University, has reviewed selected parts of the publication and submitted valuable comments. In addition, comments on the publication have also been sought through an external reviewing process, and comments were submitted by the Swedish Environmental Protection Agency and the County Administrative Board of Gävleborg.

SGI and SAO would like to give special thanks to the following people for their valuable contribution to the publication: John Collins, AquaBlok, Ltd. (U.S.A.), Pär Elander, Elander Miljöteknik AB, Henrik Eriksson, Golder Associates AB, Tore Hjartland as a representative for BioBlok Solutions AS (Norge), John Hull, AquaBlok, Ltd. (U.S.A.), Ludvig Landen, Stadsbyggnadsförvaltningen, Helsingborg, Dr. Jens Laugesen, DNV GL AS (Norge), Prof. Danny D. Reible, Texas Tech University (U.S.A.), Kevin Russell, Anchor QEA (U.S.A.), and Prof. Ian Snowball, Uppsala University.

A decision to publish this publication has been taken by Mikael Stark. Linköping, December 2016.

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SGI Publication 30-1, Huvuddokument. *In-situ* övertäckning av förorenade sediment. Metodöversikt. (In Swedish)

SGI Publication 30-1E, Main text. *In-situ* capping of contaminated sediments. Method overview.

SGI Publication 30-2E. *In-situ* capping of contaminated sediments. Contaminated sediments in Sweden: A preliminary review.

SGI Publication 30-3E. *In-situ* capping of contaminated sediments. Established *ex-situ* and *in-situ* sediment remediation technologies: A general overview.

SGI Publication 30-4E. *In-situ* capping of contaminated sediments. Remedial sediment capping projects, worldwide: A preliminary overview.

SGI Publication 30-5E. *In-situ* capping of contaminated sediments. Capping Sweden's contaminated fiberbank sediments: A unique challenge.

SGI Publication 30-6E. *In-situ* capping of contaminated sediments. An extensive, up-to-date collection of relevant technical and other international references.

SGI Publication 30-7. *In-situ* övertäckning av förorenade sediment. Övergripande sammanfattning. (In Swedish)

SGI Publication 30-7E. *In-situ* capping of contaminated sediments. Overall summary.

Fact sheet. *In-situ* capping of contaminated sediments. Method overview.

1. Introduction

The problem of contaminated sediments and risks they can pose to the environment and humans is not unique to Sweden. Contaminated sediments occur in nearly all countries to some extent, in both inland and coastal aquatic environments. And, like Sweden, most sediment contamination in most countries results from historical releases, when regulatory controls were lacking or minimal.

There is no single national inventory currently available for contaminated sediments, as there is for contaminated land[1]. However, information does exist on contaminated sediments in Sweden. Such information is distributed throughout various published documents, including in: regional programs summarizing contaminated sites, regional and national environmental monitoring programs, and risk assessments related to land-based point-sources for contaminant inputs into surface waters.

The true scale and severity of the contaminated sediment problem in Sweden is unclear. Regardless, a preliminary review of available information indicates that contaminated sediments occur in 19 of Sweden's 21 counties. Sediment-related risks at some portion of the identified sites are no-doubt at unacceptable levels, thus requiring remediation now or in the near future.

Globally-accepted technologies for sediment remediation generally rely on either removing the contaminated sediment then managing it *ex-situ*, or remediating sediment contamination in-place (*in-situ*). *In-situ* capping is an internationally recognized and accepted technology for remediating contaminated sediments, and is extensively used in other countries like the USA and Norway. In contrast, use of capping-based remedies in Sweden has been very limited to-date. There are likely multiple reasons for this.

The primary goal of this publication is to establish a basis for capping as a viable *in-situ* remediation alternative for managing contaminated sediments by compiling a technology overview and effectively disseminating overview results. As described in the next section, this publication collectively comprises a state-of-the-art review on *in-situ* capping plus several supporting publications.

Production of this publication results from collaboration between the Swedish Geotechnical Institute (SGI) and SAO Environmental Consulting AB (SAO). The main author is Dr. Joseph Jersak, with SAO and co-authors are Dr. Gunnel Göransson, Dr. Yvonne Ohlsson, M.Sc. Lennart Larsson, Dr. Peter Flyhammar and Dr. Per Lindh, all with SGI. Additionally, Professor Danny D. Reible, Texas Tech University, reviewed and provided valuable comments on selected portions of the publication.

2. Project objectives

The main objective for this project was to conduct a technically detailed, state-of-the-art review (method overview) of the remedial practice of *in-situ* capping of contaminated sediments. The main document resulting from this review can be viewed in SGI Publication 30-1E. A fact sheet on *in-situ* remedial sediment capping can be viewed here.

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[1] For clarification, Sweden's national inventory of contaminated land does not contain information on contaminated sediments.

Another objective for this project was to develop several documents to collectively support and help “make the case” for why such a state-of-the-art review is important and relevant to a wide variety of Swedish stakeholders. The SGI Publication 30-1E includes the following supporting and stand-alone publications:

- Contaminated sediments in Sweden: A preliminary review (SGI Publication 30-2E).
- Established ex-situ and *in-situ* sediment remediation technologies: A general overview (SGI Publication 30-3E).
- Remedial sediment capping projects, worldwide: A preliminary overview (SGI Publication 30-4E).
- Capping Sweden’s contaminated fiberbank sediments: A unique challenge (SGI Publication 30-5E).
- An extensive, up-to-date collection of relevant technical and other international references (SGI Publication 30-6E).

Brief summaries of the state-of-the-art review and each supporting documents are provided below.

3. State of the art review: *In-situ* capping of contaminated sediments

3.1 Introduction

Remedial sediment capping generally involves placing cap material overtop subaqueous contaminated sediment to create a new bottom substrate and to meet pre-defined objectives for long-term cap performance. Certain conditions are more favorable for capping than for other remedial technologies, and there are advantages and limitations to certain types of capping when compared to other technologies (SGI Publication 30-3E).

Contaminated sediments can be capped *in-situ* or following removal and re-deposition in another location. This state-of-the-art review focuses on *in-situ* capping, but discussions also generally apply to capping re-deposited contaminated sediments.

Two end-of-spectrum strategies for sediment capping are internationally recognized: **isolation capping** and **thin-layer capping**. The strategies differ in multiple ways, but mainly in terms of objectives for cap performance. Much of the state-of-the-art review is structured and presented around these two capping strategies.

3.2 Isolation capping: performance objectives, design & materials, and additional factors

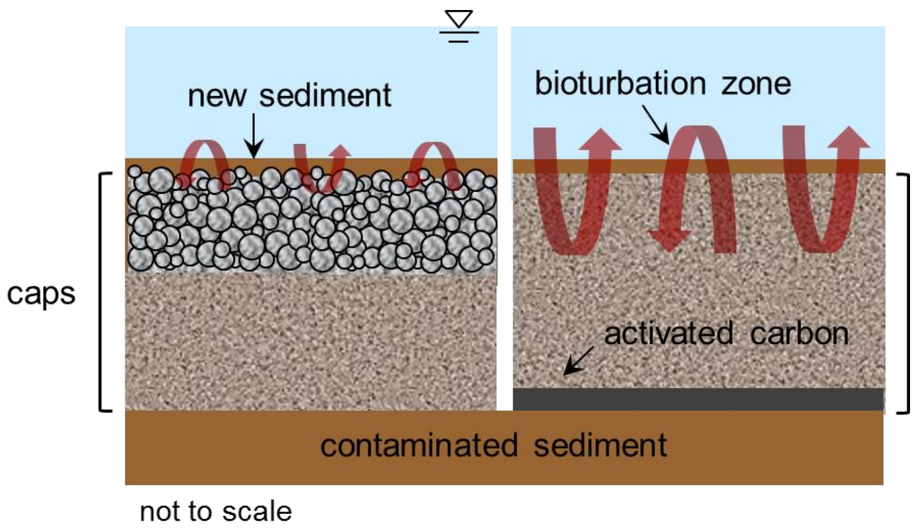
Performance objectives for isolation capping typically include:

- **Physical isolation** of bottom-dwelling organisms from direct contact with and exposure to underlying contaminated sediments.
- **Chemical isolation** of the cap's biological zone from sediment contaminants migrating up into and through the cap over time.
- **Stabilizing sediment** against erosion by natural and human-related forces.

The internationally accepted approach for designing isolation caps is use of the "layer-cake" concept. This concept involves including different material layers at pre-determined thicknesses. Each layer is intended to address or counter-act one or more processes acting on or in the cap over time (bioturbation, erosion, chemical isolation, consolidation, cap/sediment mixing, etc.).

Various natural and man-made materials are used in isolation capping. These include non-reactive conventional materials (sediment, sand, crushed stone, geotextiles, etc.) and/or more effective "active" materials. The most common active capping materials include strong sorbents like activated carbon (AC) and organoclays as well as low-permeability clay minerals. When active materials are difficult to place through water on their own, they are often incorporated into products or technologies that are easily placeable through water in a controlled manner. Internationally, the most commonly used active capping products or technologies include: AquaBlok® and BioBlok® technologies, SediMite™, Reactive Core Mats (RCMs™), and OPTICAP (a placement method).

Appropriately designed conventional isolation caps can meet performance objectives at many sites. However, site conditions occur for which active isolation caps are necessary or preferred. Such conditions can include: superior performance, equivalent performance at a lower total thickness, and/or overall cost effectiveness. Shown below are conceptual examples of conventional (left) and active (right) isolation caps.



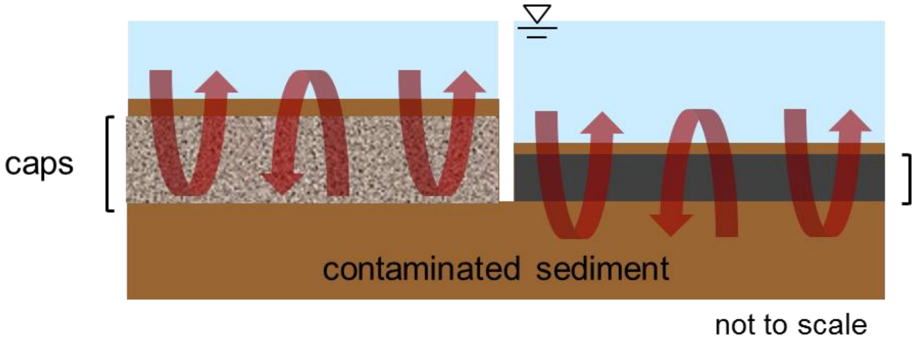
When designing and constructing conventional or active isolation caps, additional site- and sediment-specific factors should be considered, including: potential influence of groundwater upwelling, geotechnical stability (sediment bearing strength and slope stability), and gas ebullition. Possible use of geotextiles in cap design should also be carefully considered.

3.3 Thin-layer capping: performance objectives, design & materials, and additional factors

In contrast to isolation capping, the main performance objective for thin-layer capping is to reduce – but not necessarily eliminate – biological exposure to and bioaccumulation of sediment contaminants. This means that while cap thickness is greater than bioturbation depths for most bottom-dwelling organisms, some may still penetrate deeper and into underlying contaminated sediments.

The layer-cake design concept is not used in thin-layer capping. Instead, parameters controlling thin-layer cap design and thickness include: the type and reactivity of cap material used, expected bioturbation depths, and target levels for reduced exposure to and bioaccumulation of contaminants dissolved in porewaters in the cap's biological zone.

Most conventional and active materials (including products and technologies) used in isolation capping are also used in thin-layer capping. When using non-reactive (i.e. non-sorptive) materials like sand, layer thickness should at least equal the depth of the well-mixed bioturbation zone. When using strong sorbents like AC, layer thickness can be less than the well-mixed depth and still be protective. Shown below are conceptual examples of conventional (left) and active (right) thin-layer caps. Conventional thin-layer capping is often considered the same as Enhanced MNR, while active thin-layer capping is often considered the same as *in-situ* treatment.



As for isolation capping, other factors including possible groundwater upwelling, geotechnical stability, and ebullition also need to be considered when designing and constructing conventional or active thin-layer caps

3.4 Choosing the most appropriate capping approach

Various technical, economic, and other factors should be considered and balanced when choosing the most appropriate capping approach for a given site and project: Isolation or thin-layer? Conventional or active?

3.5 Cap construction

Specific objectives should be met when constructing any type of cap overtop a submerged sediment surface using loose (bulk) materials. These objectives include cap construction: in a controlled manner, in a geotechnically stable manner, and in a way that minimizes sediment re-suspension to the extent possible. Many different types of equipment can be used in different ways to meet cap-construction objectives in a range of aquatic environments and site conditions, including when capping soft sediments.

3.6 Cap monitoring

Two different types of monitoring are involved in any sediment capping project: Construction monitoring and performance monitoring. **Construction monitoring** occurs during and just after (days to weeks) cap construction to insure the cap is constructed as designed, as well as in a geotechnically stable manner. **Performance monitoring** occurs long after (months to years) the cap is in place to confirm the cap is functioning as intended over the long-term. A wide variety of equipment and techniques are used to conduct construction and performance monitoring.

Long before field phases of a capping project begin, written plans should be in place that describe key elements of construction and performance monitoring programs in detail (what, where, when, how, how many, for how long, etc.).

4. Contaminated sediment in Sweden: A preliminary review

SGI Publication 30-2E summarizes results of a preliminary review of the most up-to-date and readily available information related to the current state of knowledge regarding the type and occurrence of contaminated sediments identified in inland and/or coastal waters within each of Sweden’s 21 counties.

Contaminated mineral-based (minerogenic) and/or cellulose-bearing (“fiberbank”) sediments occur in at least 19 counties. At many sites, sediment contamination likely poses unacceptable risks to the environment and/or human health – risks that need to be effectively managed (remediated).

5. Established *ex-situ* & *in-situ* sediment remediation technologies: A general overview

A general understanding of established sediment remediation technologies is essential to more fully appreciate capping-based remedies in particular, and to place capping into the overall context of sediment remediation. Complete removal of *all* sediment contamination and at a reasonable cost would obviously always be the optimal remedial approach for any impacted site – given no limitations. However, the realities are contaminant removal is rarely if ever complete, and associated total costs are high, often prohibitively so. Thus, alternatives to removal-based remedies that are both technically- and cost-effective are often needed.

SGI Publication 30-3E introduces, describes, and generally compares proven-effective and internationally-accepted *ex-situ* and *in-situ* technologies for remediating contaminated sediments. Technologies include: removal (dredging); Monitored Natural Recovery (MNR); Enhanced MNR; *in-situ* capping and *in-situ* treatment.

6. Sediment capping projects worldwide: A preliminary overview

In-situ remedial technologies – especially different types of capping – have become increasingly more popular and widely used over the last couple decades. This is likely due in part to shortcomings inherent to removal-based remedies. Another major reason for significant international growth in sediment capping is that it works. Success in capping assumes this remedy (of some type) is appropriate for a given site, and the cap is designed and constructed in an acceptable manner.

SGI Publication 30-4E summarize results of a preliminary worldwide overview of the most up-to-date, readily available information on completed, ongoing, or planned capping projects, including in Sweden. Information was obtained and reviewed for projects involving different types of capping. The different types of capping include: isolation, thin-layer, conventional, and active (see SGI Publication 1E).

Over 180 capping projects (in different forms) have been completed, initiated, or planned worldwide over the last several decades, most in the U.S. and many in Norway. Six capping projects have been conducted to-date in Sweden. Virtually all projects worldwide have involved capping contaminated minerogenic sediments. This global track record illustrates capping is a versatile and internationally-established sediment remediation technology – at least for minerogenic sediments.

7. Capping Sweden's fiberbank sediments: A unique challenge

The phrase "fiberbank sediments" includes fiberbank deposits as well as fiber-rich sediments. Fiberbank deposits inherently contain multiple contaminants, are nearly pure cellulose in composition, and result from past discharges from pulp and papermill industries. In contrast, fiber-rich sediments – which are often located adjacent to fiberbank deposits – are a mix of fiberbank deposit material and minerogenic (mineral-based) material. Fiberbank sediments are a significant problem in Sweden both in terms of their abundance and broad distribution (SGI Publication 30-2E) and because of the unacceptable risks they likely pose at many sites.

Theoretically, one or more types of capping should be appropriate for remediating many fiberbank sediment sites, as capping is for remediating contaminated minerogenic sediments. However, the fact remains there is very little global project experience to-date in capping these anthropenically-derived sediments. Because of this lack of experience – coupled with the sediments' unique characteristics – there are many unknowns related to how fiberbank sediments will respond to different types of capping remedies and how well caps will function over the long-term.

SGI Publication 30-5E outlines some of the unknowns related to remedial *in-situ* capping of fiberbank sediments.

8. Overall conclusions

- Contaminated minerogenic sediments have been identified in at least 17 of Sweden's 21 counties. Contaminated fiberbank sediments have been identified in at least 10 counties. Sediment contamination is clearly a national problem – not just a local or regional problem.
- Sediment risk assessments have been conducted at some Swedish sites. At most sites, risks have been classified at high to very high levels, indicating sediments need to be remediated. Sediment risk assessments and classifications are still needed at many sites, beyond just identifying contaminant occurrence. When these assessments and classifications are completed, the need for sediment remediation at many more sites in Sweden will likely become evident.
- Proven-effective and internationally-accepted ex-situ and *in-situ* technologies are available for remediating contaminated sediments. These include: removal (dredging), MNR, EMNR, *in-situ* capping, and *in-situ* treatment. Each technology has recognized advantages and limitations relative to the others.
- Results of a preliminary review indicate only a small number of contaminated sediment sites have been remediated so far in Sweden, a total of less than 20. As noted above, this is probably a small fraction of the total number of sites requiring remediation, nationwide.
- Most sediment remediation conducted to-date in Sweden has been through removal by dredging (approx. 10 projects) (note: this does not include projects involving maintenance dredging, mainly for navigational purposes). Fewer sites have been remediated using some form of capping (six projects).
- Given no limitations, complete removal of all sediment contamination and at a reasonable total cost would obviously be the optimal remedial approach at any site. However, the realities are contaminant removal, e.g. by dredging, is rarely complete and associated total costs are typically high, often prohibitively so. Thus, technically- and cost-effective alternatives to removal are needed.
- *In-situ* remedial technologies – especially capping – have become increasingly more popular and widely used over the last two to three decades. This has resulted in part from shortcomings inherent to removal-based remedies. Another major reason for significant international growth in sediment capping is that it works.
- Capping is a flexible remedial technology in that different capping strategies (isolation and thin-layer) and different cap materials (conventional and active) can be combined and successfully applied to a broad range of contamination and site conditions.
- Over 180 capping projects, in different forms, have been completed, initiated, or planned worldwide over the last several decades, most in the U.S. and many in Norway. Virtually all projects involve contaminated minerogenic sediments. Such a global track record confirms capping is indeed an internationally established sediment remediation technology, at least for minerogenic sediments. Thus, capping is not new, novel, and/or untested, and should not be regarded as such.

- Theoretically, capping (in one or more forms) should also be appropriate for remediating many of Sweden's contaminated fiberbank sediment sites. However, global experience in capping these unique, anthropenically-derived sediments is extremely limited. Because of this lack of experience – coupled with the sediments' unusual characteristics and attributes – there are many unknowns related to how fiberbank sediments will respond to different types of capping remedies, including how well capping remedies will function for fiberbank sediments over the long term.
- When capping contaminated minerogenic or fiberbank sediments at coastal sites, consideration should be given to how best to design capping-based remedies that will remain effective over the long-term, even when sea-level changes and/or land uplift results in significant changes to site conditions (water depths, aquatic erosion regimes, submerged slopes, etc.).

The following points in particular should be emphasized:

- Capping in general will not be an appropriate remedy at a number of sites, for various reasons. Furthermore, when capping is considered appropriate for a given site, some types of capping will likely be more appropriate than others (while some types may not be appropriate at all). Whether or not capping is an appropriate remedy and, if so, which type and cap design is most appropriate, are all decisions that must be made on a site- and project-specific basis.
- Cap monitoring should be conducted during and after construction, to insure the cap is constructed according to specifications and is performing over time as intended.
- No single sediment remediation technology – including capping – is "one-size-fits-all" and thus appropriate for all sites and projects. There should also not be a pre-conceived notion a particular technology, like dredging or capping, is best for a given site. Selecting which remediation technology or technology combination is most appropriate is a site- and project-specific process. This remedy selection process must systematically consider and balance many different and sometimes conflicting factors, not just costs.
- No sediment remedy or remedy combination – regardless of how well it is designed and implemented – will protect a site over the long-term if significant contaminant inputs continue after remedy implementation. Thus, identifying and controlling contaminant sources is a critical step, and preferably one taken before sediment remediation occurs.
- Due to both the technical complexity and the high costs associated with complete removal of contaminated sediments from aquatic environments, there will be a significant number of sites where this is not considered a realistic option. Risks posed by sediment contamination will instead, in many cases, need to be effectively managed in-place. *In-situ* capping, in its various forms, is one proven technology that can be an option in these cases.

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