Resilient Remediation of Radioactively Contaminated Sites, Long-term Stewardship and Institutional Control: Challenges to Developed and Developing Countries

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A preamble

It is estimated that the global market for environmental remediation is worth US$ 142 billion in 2025 with an estimated growth close to US$ 500 billion in 2034 (CAGR ~ 15%) (Precedence Research);

It is estimated that the remediation of radioactively contaminated sites accounts for 10% of the whole market giving a figure of US$14 billion

For decommissioning of Nuclear Reactors, the market is worth US$ 7.4 billion in 2025 (btw, remediation of these sites also included). Market is expected to grow about US$ 13.4 billion by 2037 (CAGR ~ 5%)

This estimate reflects the critical, albeit niche, role of radioactive remediation within the broader environmental sector, especially in regions with

- Uranium Mining and NORM Legacy Sites;
- Areas with contamination of residues of the O&G operations;
- Decommissioning of Nuclear Power Plants;
- Industrial and Military Facilities.
- Areas affected by Nuclear Accidents

The private sector is expected to witness the fastest growth during the projected period;

This growth can be attributed to the increasing sustainability commitments among business and industrial stakeholders.

To remain compliant with regulations, factories, oil refineries, and construction companies are making significant investments in remediation.

As the importance of Environmental and Social Governance practices grows companies are initiating remediation projects early on—not merely as a regulatory requirement, but as a strategic business advantage;

The private sector is rapidly adopting data-driven remediation techniques and sustainable cleanup methods to support informed decision-making, enabling faster implementation of remediation solutions.

The IAEA Framework for Remediation

Planed Exposure Situations

- Limits to members of the public are established in terms of annual effective dose
  - 1 mSv/y
  - Dose constraint of 0.3 mSv/y
  - Optimization down to 10 microSv/y

Existing Exposure Situations

- Should be justified i.e. do more good than harm
- Use of Reference Levels (1 – 20 mSv/y)
- Keep optimization in mind – ALARA but consider social and economics
- Focus is on reducing doses

The situation in the USA

1. EPA's Risk-Based Cleanup Goals:

- **Residential exposure scenario**: The target is typically a **cancer risk range of 1 in 10,000 to 1 in 1,000,000** (i.e., 10^{-4} to 10^{-6} excess lifetime cancer risk).
- **Dose-based criteria**: Often, the EPA aims for a **maximum residual dose of 15 millirem/year (0.15 mSv/year)** for the reasonably maximally exposed individual, plus **ALARA** (As Low As Reasonably Achievable) principles.

2. DOE Guidelines (for Former Nuclear Sites)

- **Public dose limit**: **≤ 25 millirem/year (0.25 mSv/year)** from all pathways.
- **Groundwater protection**: Must meet **Safe Drinking Water Act** standards (e.g., **4 millirem/year** for beta/gamma emitters).
- **Surface contamination limits**: Based on radionuclide-specific criteria

The situation in the USA (cont.)

3. NRC Standards (for Decommissioning Nuclear Facilities)

- **10 CFR Part 20 Subpart E**: Limits residual radioactivity to allow **license termination**.
- **Dose criterion**: ≤ **25 millirem/year (0.25 mSv/year)** for unrestricted use, with ALARA considerations.

4. CERCLA (Superfund) Sites

Under the **Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)**:

- Cleanup levels are based on **risk assessments**, **Applicable or Relevant and Appropriate Requirements (ARARs)**, and **site-specific conditions**.
- **Institutional controls** may be used if unrestricted use is not feasible.

A definition

- In essence, resilient remediation is about **future-proofing environmental remediation** — ensuring that remediation efforts are not only effective today but remain robust and beneficial in the face of tomorrow's challenges.

What does Resilient Remediation Entail?

Climate Adaptation: Traditional remediation assumes stable environmental conditions. Resilient remediation, however, anticipates impacts like rising sea levels, increased rainfall, droughts, and temperature shifts that could compromise cleanup efforts.

Sustainability Integration: It combines principles of sustainable remediation—minimizing environmental impact and maximizing social and economic benefits—with climate resilience.

Adaptive Management: Strategies must be flexible and responsive, incorporating monitoring and iterative adjustments to remain effective over time.

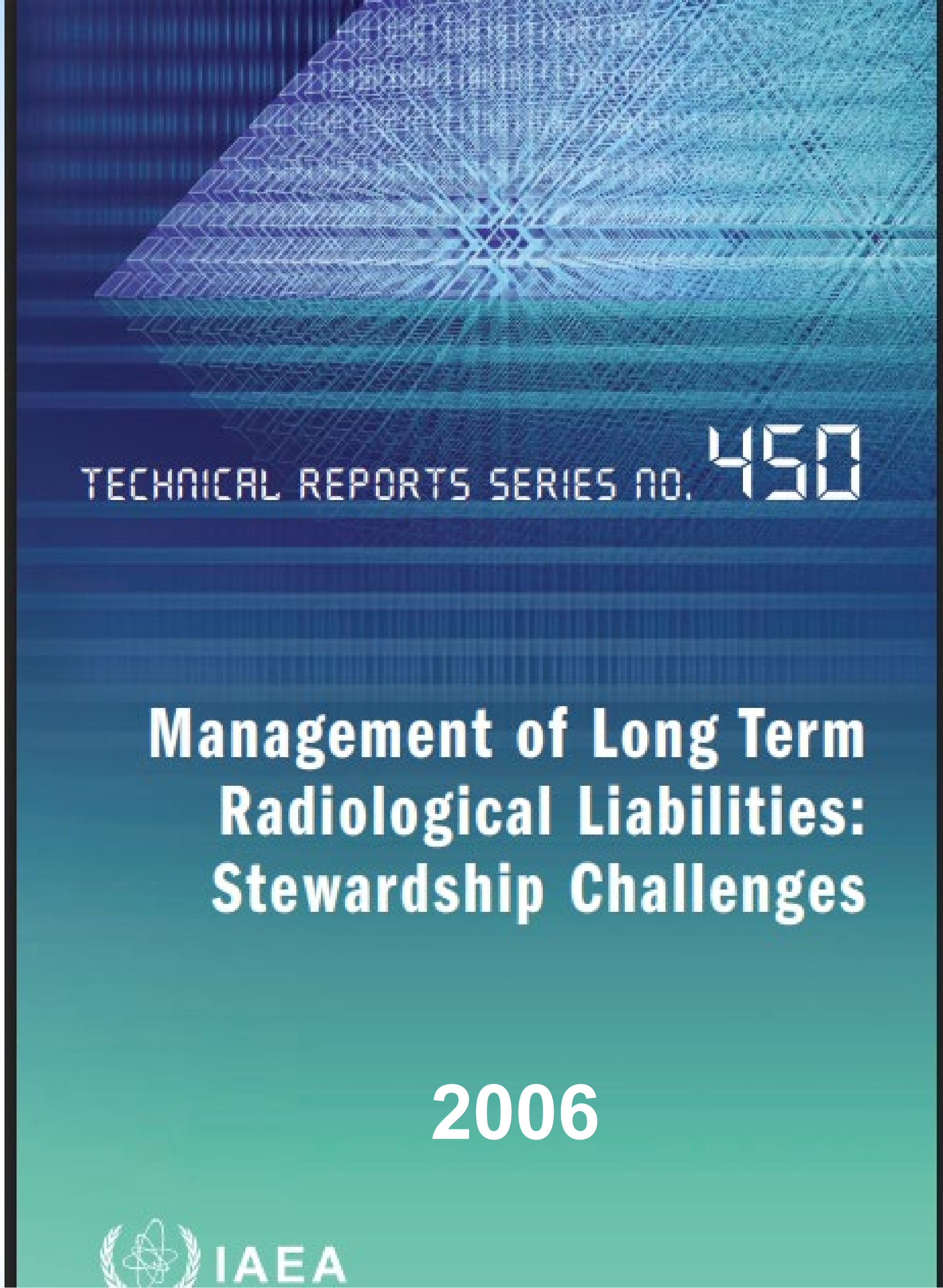
Ecosystem-Based Solutions: Nature-based approaches are often more resilient and cost-effective than engineered solutions.

Community Value: Resilient remediation also considers social vulnerability, aiming to protect public health and create community benefits like jobs, green spaces, and clean energy infrastructure.

Key Messages:

- **Being Adaptive**
- Focusing on Realistic Time Frames
- **Keeping Stakeholder Involved**
- Allowance for Economic Changes
- **Engineering with Nature**
- Keeping Records Alive
- Monitoring

Did things change that much from 2006 to 2025 ?



Long Term Stewardship x Institutional Control

Long-Term Stewardship (LTS) in the context of **Environmental Remediation** refers to the set of actions, controls, and responsibilities necessary to ensure that **remediated sites remain protective of human health and the environment** over extended periods—often decades or longer;

Institutional Control - Control of a site by an authority or institution designated under the laws of a State. This control may be active (monitoring, surveillance, remedial work) or passive (land use control) – IAEA Safety Glossary 2022. If institutional control after the closure of a facility (or site) is deemed to be necessary, ***the responsibility for maintaining institutional control shall be clearly assigned***.

Challenges in Developed Countries

Aging Infrastructure and Legacy Contamination

Developed countries struggle with risks from aging infrastructure and contamination from past industrial activities.

Regulatory Complexity

Complex regulations can delay decisions and slow remediation implementation in contaminated sites.

Public Trust and Transparency

Building public trust requires transparency and stakeholder engagement in remediation efforts.

Funding and Political Will

Sustaining funding for long-term cleanup demands political support and budget prioritization.

The situation in developed countries – focus on the USA

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Superfund Task Force (2017):

Develop Strategies Toward Deletion from NPL,

Broaden the Use of Adaptive Management,

National Consistency,

Clarify Priorities and Principles,

Focus on Optimization,

State of The Art Technologies,

Facilitate Site Redevelopment,

Engage Communities

NAS (2019):

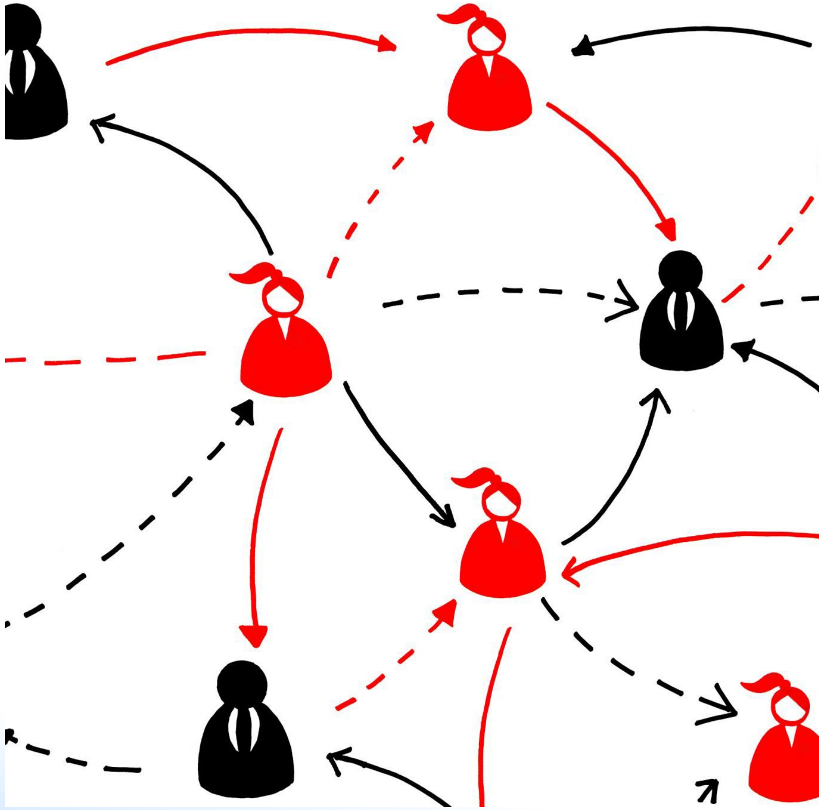
Activities Are Site-Based, Contractor-driven and Managed,

Have a Short-Term Focus on Addressing Technical Challenges In Existing Cleanup Projects

GAO Highlights (2025):

Collect Information Specific to Scope, Schedule and Cost of Cleanup to Enhance Technical and Policy Support and Inform Prioritization Decisions To Reduce Risk;

Challenges in Developing Countries



Technical and Financial Limitations

Developing countries face limited technical capacity and financial constraints in addressing environmental contamination effectively.

Governance and Institutional Gaps

Weak governance structures and institutional gaps hinder enforcement and coordination in contamination remediation efforts.

Need for International Cooperation

International support is essential to build capacity, share resources, and train professionals in developing countries.

Community Engagement and Stewardship

Socio-economic pressures and competing priorities complicate local community involvement and long-term remediation stewardship.

Challenges in Emerging Countries

92% of pollution related mortality occurs in low- and middle-income countries (Hardoy et al 2001, Landrigan et al, 2018)

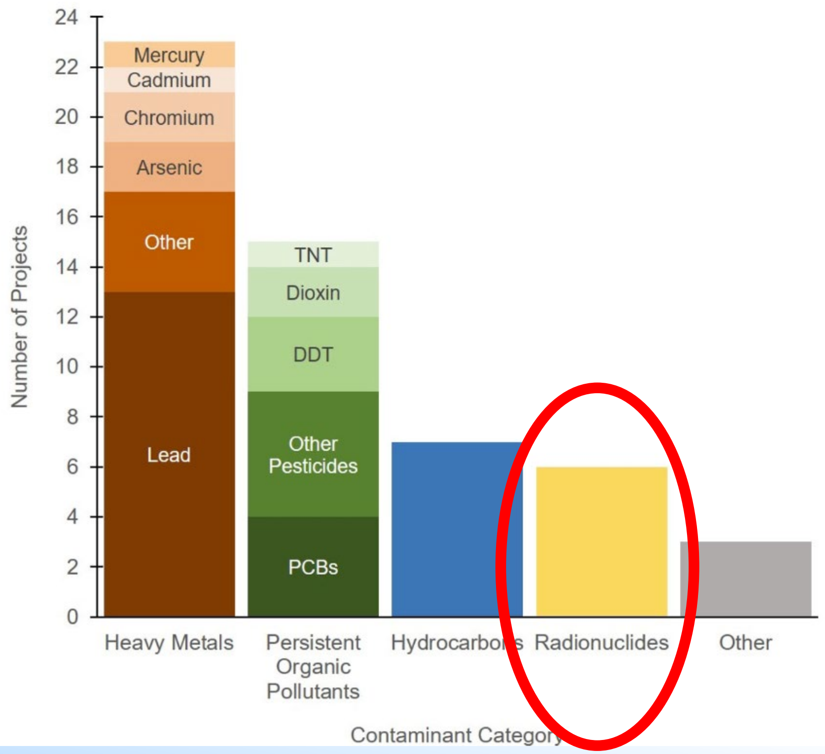
Institutional Controls rely on compliance and participation from the public, offering additional support to include local stakeholders within project activities (O'Brien et al. 2020);

Lack of funding and responsibility gap in emerging countries lead to limited governmental capacity to regulate and control remediated sites and provide for appropriate institutional control;

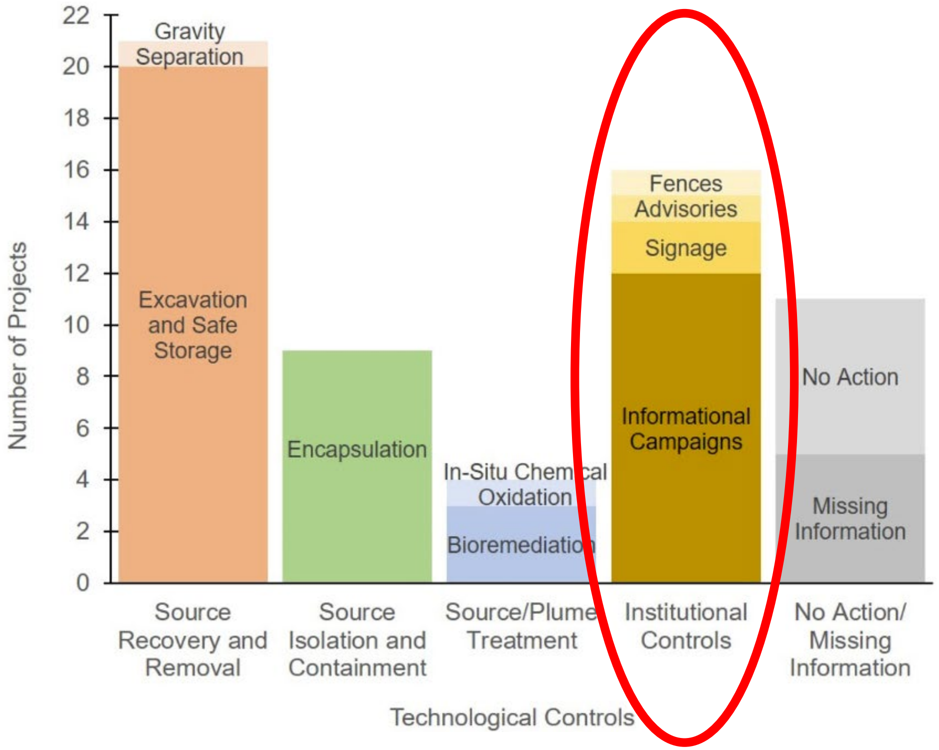
This situation is aggravated in climate changing conditions in which remediation solutions may depend on active control over long periods of time.

Remediation in developing countries (O’Brien, S. 2021)

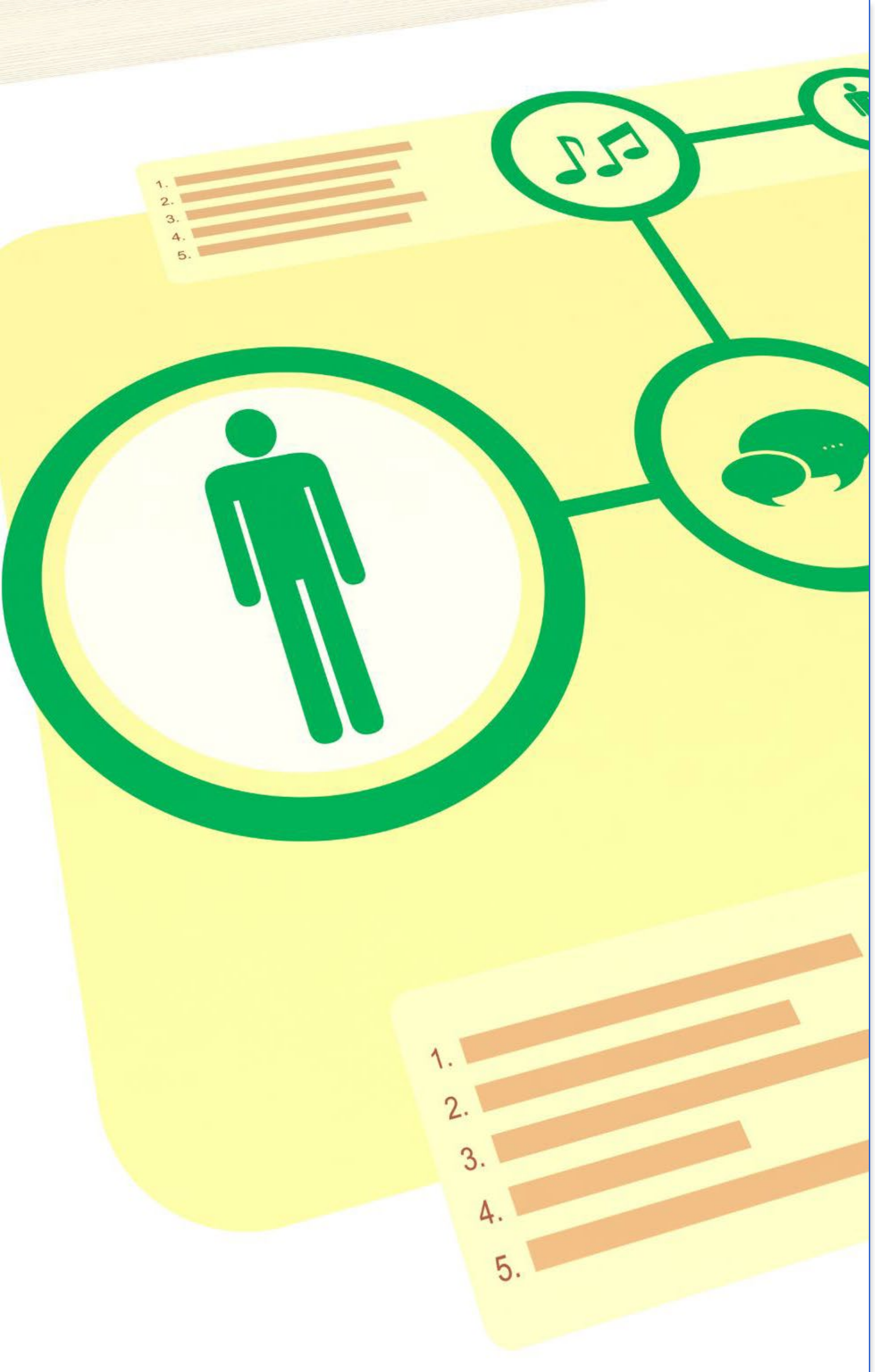
Number of remediation projects sorted by targeted contaminant



Remediation projects sorted by employed remedial strategy



STRATEGIC SOLUTIONS AND RECOMMENDATIONS



Adaptive Management Strategies

Real-Time Monitoring

Implement real-time monitoring systems to track contamination and environmental changes continuously.

Scenario Planning

Use scenario planning to anticipate future risks and adjust remediation plans proactively.

Feedback Integration

Establish feedback loops to integrate new data and stakeholder input into decisions effectively.

Flexible Regulations

Adopt flexible regulatory frameworks to enable timely responses to emerging challenges and innovations.

Community Engagement Solutions

Local Advisory Boards

Establishing local advisory boards includes community members in decision-making to build trust and collaboration.

Public Education Campaigns

Education campaigns raise awareness about risks and safety, empowering residents to participate actively in remediation.

Transparent Environmental Data

Sharing environmental data and progress promotes accountability and encourages informed community dialogue.

Relocation Support Services

Providing compensation and support mitigates social and economic impacts when relocation is necessary.

Technology Deployment

Advanced Surveillance Technologies

Remote sensing and drones provide detailed site mapping and improve data accuracy for remediation efforts.

In-Situ Remediation Methods

Bioremediation and vitrification offer cost-effective, eco-friendly solutions for contamination treatment.

AI for Predictive Modeling

Artificial intelligence and machine learning optimize intervention strategies by predicting contamination spread.

Technology Transfer Programs

Technology transfer initiatives ensure access to innovations, supporting global equity in environmental management.

International Cooperation Frameworks

Global Partnerships

Collaboration with organizations like IAEA and UNEP boosts access to expertise and funding for contamination remediation.

Knowledge Exchange Networks

Global networks facilitate sharing of successful remediation experiences and best practices among countries.

Technical and Financial Support

International donors provide technical assistance and funding to help developing countries build remediation capacity.

Standardization and Protocols

Harmonized standards ensure consistent and high-quality remediation efforts across international borders.

Recommendations

Developed Countries Focus

Modernize infrastructure, invest in resilient technologies, and secure environmental trust fund financing for long-term remediation efforts.

Developing Countries Priorities

Enhance capacity building via education and training, establish legal frameworks, and utilize international aid and technology transfer.

Inclusive Remediation Strategies

Integrate adaptive management, community engagement, and international cooperation for sustainable environmental outcomes.

Conclusions

Global Cooperation Importance

Successful remediation of radioactive sites requires global cooperation and strategic planning for sustainable outcomes.

Long-Term Stewardship

Long-term stewardship and institutional control are vital to ensure sustainable environmental management.

Tailored Solutions

Addressing technical, financial, and governance challenges requires solutions adapted to developed and developing countries.

Integration for Resilience

Adaptive management, community engagement, technological innovation, and cooperation enhance remediation resilience.

THANK YOU SO MUCH FOR YOUR ATTENTION