Remediation of Uranium Mining and Milling Tailing in Mailuu-Suu District of Kyrgyzstan

FINAL REPORT

Authors:

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Remediation of Uranium Mining and Milling Tailing in
Mailuu-Suu District, Kyrgyzstan

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EXECUTIVE SUMMARY

1 Introduction

The Mailuu-Suu District of uranium ore mining and milling is located about 60 km north-west of Jalal-Abad and about 25 km from the border with Uzbekistan. Uranium mining and milling activities started 1946 and lasted until 1968. Tailings (residues from ore processing) and of low-grade ore and waste rocks from mining, covering an area of approximately 44 hectares and with an estimated volume of about 3 million m³ were deposited in moderate mountainous terrain and gently sloping alluvial areas, often in close proximity to the Mailuu-Suu-, Kara Agach-, Kulmensai and Ailampa-Sai Rivers. Radioactive substances were stored in 23 tailings and 13 mine waste dumps. The stability of many tailings is at risk. Attention is mostly directed to Tailing n°3, because of its important radionuclide inventory, its suspected limited stability and since threatened by the borders of a major landslide.

Due to the mountainous topography especially in the upper reaches of the regional drainage pattern, the rivers and adjacent areas are subject to major flood conditions, primarily during spring run-off. Therefore significant damage evidence for high water erosion potential can be observed all along the river banks.

Also evidence for significant landslide activities and of slope instability and movement can easily be observed throughout the area causing damage of roads, power lines, pipelines and housing and in some cases of tailings impoundments. In several cases this has resulted in the relocation of infrastructure and population. Major landslides potentially affecting directly or indirectly uranium ore processing tailings deposited along the Mailuu Suu River valley (i.e. tailings deposits No. 3, 9, 10, 8, 5 and 7) are the Tectonic, Technicum, Isolit and Koetash landslides which partly already caused river blockages in previous times (such as Tectonic Landslide in 1992). A recent reactivation this spring (2002) of the southern limb of the Tectonic landslide again caused partial blockage of the Mailuu Suu River. Earthquakes may have a direct or indirect effect on mudflows or landslides.

2 Project approach, scope and added value

The objective of the EC-TACIS funded project is to evaluate measures to be taken by the authorities to reduce the radiological exposure of the population and to prevent environmental pollution by radionuclides and heavy metals in case of loss of tightness of dams and damage to dumps and heaps from mining and milling by land and mudslides and to propose sustainable remedial options.

The specific project objectives are (1) to identify the risks (radiological and others), (2) to propose measures to monitor and to mitigate those risks, (3) to study and evaluate rehabilitation plans for Tailing 3 and evaluate how the approach for Tailing 3 can be applied to other tailings, (4) to implement short term remedial measures on Tailing 3, (5) to study and evaluate rehabilitation plans to decrease the impact of a disaster scenario.

The outputs/sustainable results are (1) the improvement of knowledge on risk situation at Mailuu Suu, (2) the improvement of the situation at Tailing 3, (3) improved environmental protection (4) improved monitoring and prevention systems, (5) a feasibility study for a number of remedial options which can be used as basis for decision taking, (6) improved information and awareness of the population.

This was achieved through: (1) stock taking of already existing data and collection of new data (sample collection and analysis), (2) selection, procurement and installation of monitoring and prevention devices and equipment, (3) assessment of risks and recommendations for actions, (4)
short term risk preventive measures for potential disaster scenarios, (5) implementation of a pilot project to mitigate the short-term risks posed by Tailing 3, (6) proposing a short-, mid- and long-term remediation approach (7) explaining the risks to the local population.

3 Results of monitoring and actual radiological situation

A radiological monitoring campaign was set-up by SCK-CEN in order to assess among others, the actual radiological situation and to assess the actual radiological exposure.

3.1 Results of radiological monitoring campaign for prioritisation of fencing off of tailings

3.1.1 Gamma exposure on tailings

In August 2001 all tailings, parts of Kara Agach (waste dump) and parts of waste dumps 1 and 2 were screened for gamma exposure.

The background gamma exposure recorded is in the range of 60-110 nSv/h.

For most of the tailings, for most of the surface, the exposure is around background or a factor two higher. At tailing 3, the borders of tailing 4, tailing 5, 11, 13, 18 and 21 higher dose rates were noted. At the waste dump bordering T13 dose rates up to 19300 nSv/h were recorded!

Most relevant dose contributions to the local population from the tailings are direct irradiation from radium and its daughter products during occasional stays at the tailings. Inhalation of re-suspended dust and of emanated radon, were found minor contributors to the dose. As a consequence it was concluded that only the measured external dose rate needs to be considered when making a ranking of the tailings with respect to the need for their fencing off.

If we would consider an extremely conservative scenario, someone staying at the place of maximum exposure during 2h/day, the exposure rates would be higher than 1 mSv/a for 5 tailings: Tailing 3: 2.12; the dam of Tailing 4: 1.36; Tailing 5: 4.2; Tailing 13: 13.62 and Tailing 18: 3.53. To conclude, we may state that only the measured external dose rate needs to be considered when ranking the tailings with respect to the need for their fencing off.

Kara Agach represents a special case. At the ore dump site in the middle of at Kara Agach, there is a house with garden and a house under construction. The dose rates range between 130 and 1500 nSv/h (hot spots). If a person would reside 100 % of his time in this area with an external exposure rate of the mean gamma exposure (495 nSv/h, which includes the hot spots) recorded at Kara Agach, the dose by gamma exposure would be 204 mSv/a! Gamma monitoring measurements with TLD (see further) however showed that the annual mean gamma dose for the most inflicted house is 185 nSv/h. The dose to gamma exposure is hence a factor 3 lower (~70 nSv/h) yet still high if people reside full time in the house. It is considered important that the inhabitants are informed and should be advised to move from the location if the dose would be as high as in this preliminary evaluation.

3.1.2 Gamma monitoring campaign with environmental TLDs

A gamma monitoring network was set up comprising 65 measurement points (tailings, rock piles, in Kara Agach and Mailuu Suu (for both outside and in houses). Most of the dosimeters were stolen. From the remaining measurements following could be concluded.

The average exposure in the vicinity of Mailuu Suu (137 nSv/h), at Kara Agach which is partially situated on a former mining dump (158 nSv/h) and on the tailings (144 nSv/h) is somewhat higher than the control (the dosimeters stored in lead containers (117 nSv/h). There is hence a slight increase in exposure compared to the control corresponding to an additional
annual exposure of, respectively, 0.17, 0.36 and 0.24 mSv/a in Mailuu Suu, Kara Agach and on the tailings if continuous residing. As a comparison, the German Radiation Control Commission dealing with the problematic of the uranium mining and milling in former Eastern Germany (Saxony, Thuringia and Saxony Anhalt: former WISMUT activities) applied as general radiological protection principles for unrestricted use of areas and houses an additional potential radiation exposure of 1 mSv/a (effective dose) due to mining and milling activities.

3.1.3 Radon monitoring

Radon monitoring was performed during one year (two six-monthly measurements) on 50 different locations in Mailuu Suu. 31 detectors were placed on the tailings to assess the effect of the radon exhalation, 7 on miscellaneous outdoor locations and 12 detectors were installed in buildings, mostly dwellings to get an idea of the indoor radon exposure of the inhabitants. Most outside placed radon detectors were stolen.

The remaining 13 measurements outdoors ranged from 22 to 1240 Bq/m³ with an average of 280 Bq/m³ and a median of 160 Bq/m³. These are high values but not unusual for tailing ponds. The average value is very much influenced by the two high values of 710 and 1240 Bq/m³ for the second exposure period on tailing 13.

The 23 measurements indoors ranged from 60 to 6500 Bq/m³ with an average of 448 Bq/m³ and a median of 140 Bq/m³. The high value in Kara Agach of 6500 Bq/m³ was not confirmed during the second period (420 Bq/m³) making the result doubtful. Ignoring the high value results in an average of 173 Bq/m³ and a median of 130 Bq/m³. These are normal values for radon prone areas. UNSCEAR's world average for indoor radon is 40 Bq/m³.

Regarding radon levels in housed, the European Commission (1990) recommends 400 Bq/m³ as action level for existing buildings and 200 Bq/m³ for new houses. This means that according to these guidelines action should be taken at the house in Kara Agach with high radon levels. Simply by increased ventilation the radon level in the house can decrease.

In Schneeberg (WISMUT activities in former E. Germany) 50 % of the dwellings had radon concentrations exceeding 250 Bq/m³, which was the value set by SSK as the upper limit of the normal range of indoor radon concentrations.

3.1.4 Environmental sampling

3.1.4.1 Borehole samples

In August 2001, borehole samples were taken by Kyrgyz GIIS at tailing 3 (4 boreholes), tailing 7 (2), Tailing 5 (1) and Tailing 8 (1). In August 2002, 4 boreholes were made in Tailing 15 (potential alternative disposal site). Samples were analysed for physical parameters for determining tailing stability. Samples were also analysed for U, total alpha, radium, Th, Pb, some heavy metals for assessing the contaminant content and also gamma rate was measured. Samples were further analysed for dispersion relevant parameters.

Average U-concentration at tailing 3 is 231 ppm (range ~ 50 --~500 ppm). The average concentration is 232 ppm for the 4 boreholes and 290 ppm for the most contaminated borehole.

The alpha activity at the tailings is much more variable ranging from ~ 20 Bq/g to 1200 Bq/g. The average concentration is 221 Bq/g for the 4 boreholes and 591 Bq/g for the most contaminated borehole. The average radium concentration is respectively 90 Bq/g and 216 Bq/g. For the other tailings the uranium concentration is around 100 ppm and the alpha activity ranges from 5-100 Bq/g (Table ES.1.)
Table ES-1: Average radionuclide concentration and gamma dose at the tailing boreholes.

<table>
<thead>
<tr>
<th>Tailing</th>
<th>U, ppm</th>
<th>Alpha Bq/g</th>
<th>Ra-226 Bq/kg</th>
<th>Pb-210 Bq/kg</th>
<th>Th-232 Bq/kg</th>
<th>Gamma sample nSv/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tailing 3, all boreholes</td>
<td>Average</td>
<td>231</td>
<td>221</td>
<td>89609</td>
<td>29721</td>
<td>8530</td>
</tr>
<tr>
<td></td>
<td>Stdev</td>
<td>160</td>
<td>312</td>
<td>122119</td>
<td>33951</td>
<td>7675</td>
</tr>
<tr>
<td>Tailing 3, most cont. borehole</td>
<td>Average</td>
<td>290</td>
<td>591</td>
<td>216180</td>
<td>62217</td>
<td>12389</td>
</tr>
<tr>
<td></td>
<td>Stdev</td>
<td>191</td>
<td>429</td>
<td>122962</td>
<td>34876</td>
<td>4574</td>
</tr>
<tr>
<td>Tailing 5</td>
<td>Average</td>
<td>113</td>
<td>5.3</td>
<td>1813</td>
<td>923</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>Stdev</td>
<td>26</td>
<td>0.5</td>
<td>989</td>
<td>772</td>
<td>5</td>
</tr>
<tr>
<td>Tailing 7</td>
<td>Average</td>
<td>88</td>
<td>59</td>
<td>19631</td>
<td>11551</td>
<td>12570</td>
</tr>
<tr>
<td></td>
<td>Stdev</td>
<td>44</td>
<td>29</td>
<td>11615</td>
<td>6167</td>
<td>11303</td>
</tr>
<tr>
<td>Tailing 8</td>
<td>Average</td>
<td>129</td>
<td>58</td>
<td>15529</td>
<td>9283</td>
<td>7674</td>
</tr>
<tr>
<td></td>
<td>Stdev</td>
<td>56</td>
<td>26</td>
<td>6690</td>
<td>3713</td>
<td>7687</td>
</tr>
<tr>
<td>Tailing 15</td>
<td>Average</td>
<td>128</td>
<td>37</td>
<td>13130</td>
<td>6924</td>
<td>17333</td>
</tr>
<tr>
<td></td>
<td>Stdev</td>
<td>79</td>
<td>44</td>
<td>20804</td>
<td>8656</td>
<td>7522</td>
</tr>
</tbody>
</table>

It should be mentioned that only a limited number of boreholes were made and sampled. For tailing 3 the number may have been more or less sufficient to have a rather good estimate of the tailing radionuclide content. For the other tailings more extensive sampling is recommended to have such estimate. For effective remedial works on Tailing 3, certainly in case of relocation of the tailing also additional boreholes should be samples.

If we consider a volume of 110000 m³ for Tailing 3 and a dry density of 1.6 kg/L and considering the radioactivity concentrations presented in Table ES-1, the total expected alpha activity in the tailing considering the most contaminated borehole is 1.04 *10^{14} Bq and for the average of 4 boreholes 3.89*10^{13} Bq. For uranium these figures are 6.38*10^{11} Bq and 5.08*10^{11} Bq, respectively. The figures for the alpha levels correspond well with the figures presented by Geopribor (2000) who mentioned 0.7-1*10^{14} Bq in expected total alpha content. Our measured U levels are smaller than the 4*10^{13} Bq in expected total uranium content mentioned by these authors. Most of the alpha activity of the tailings can be contributed to the radium activity and only to some extent to the presence of U.

With regard to the heavy metals content, Mn levels are very high which is due to the technology of uranium ore processing using MnO₂ as oxidant.

3.1.4.2. Soil samples

Soil samples were taken at locations with elevated gamma radiation at the tailing surface or at the village of Kara Agach, built on a waste dump. As a rule vegetation samples were taken at the place of the soil samples.

Limits for uranium, radium and alpha are clearly exceeded. All the samples were taken at locations with elevated gamma radiation, so this is certainly not a presentation of the average situation but rather a worst case scenario. The soil analysis results confirm that T3 T5, T7, T4 should certainly be fenced but also at other tailings trespassing by people and animals should be hindered.

More importantly, also at Kara Agach all soil samples measured exceeded the limits for uranium and radium with about a factor 20 for uranium (79-380 ppm) and with a factor between 8 and
~1600 for radium (555-145000 Bq/kg). Here again, soil samples were taken at locations with elevated gamma radiation and so rather extreme worst-case scenarios are represented. Cultivation of food crops and animal fodder should be prohibited at Kara Agach. Children should not play on these soils!

For the one background sample taken (at Mailuu Suu town, Intourist Hotel garden) contamination levels are at least a factor 20 lower than what is observed for the Kara Agach soil so food crops can be grown there safely.

Generally heavy metal contents are below the limits.

All vegetation and crops sampled on the tailings and in Kara Agach exceed the limits for alpha, uranium and radium!

3.1.4.3 Surface water and sediments

Sediment samples and water samples were taken at the river Mailuu Suu.

There are no specific limits for sediments but the sediment concentrations are around or above the limits for surface soil. There was no trend in contaminant concentration along the Mailuu Suu for the sediments.

There is clearly an increase in the uranium concentration in the river water with distance from the water reservoir and there is clearly a loading from the leaching from the tailings and the uraniferous background rock (from 1.9 till 7.1. µg/L). The values are always a factor 1000 lower than the limits proposed for Kyrgyzstan (1.8 mg/L).

3.1.4.4. Drinking water and food

The U in the drinking water at Mailuu Suu, with provenance from the sediment collection bassin, was below the concentration limit for drinking water.

Food collected at Mailuu Suu or neighbouring villages from local people or at the market had uranium concentrations that were below the exemption limit for human consumption. The alpha concentrations are around the exemption limits for vegetation. Sometimes the limits are exceeded, generally when the origin of the sample is in Kara Agach. People living at Kara Agach should be advised not to use locally grown or reared food stuffs.

3.1.4.5 Conclusions

Regarding the exposure at the tailings, consider an extremely (unrealistic) conservative scenario (stay at place of maximum exposure during 2h/day every day of the year), the additional exposure rates would be higher than 1 mSv/a for 5 tailings: Tailings 3, 4, 5, 13 and 18 with total external exposure dose rates from 1.36 to 13.62 mSv/a). For more realistic less conservative scenarios, exposures are lower than 1 mSv/a, except sometimes for T13. To conclude, we may state that one tailing certainly needs fencing off: the dump next to tailing 13. It is however advisable to fence off all the tailings since they contain radioactive material. In case of funding limitations, we would recommend to start the fencing on tailings 3, 5, 18, 13 (certainly waste dump next to tailing 13) and the dam of tailing 4.

The results for the tailing boreholes are used for the calculations of the leaching from tailing 3. All data on gamma exposure, radon exposure, activity levels in soil, water, vegetation, food etc are used for the radiological dose calculations.

- The actual gamma and radon values recorded are not exceptional for uranium mining areas. External radiation and radon levels are normal for uranium mining areas. Additional external exposure above background is smaller than 0.4 mSv/a. The radon level in one house in Kara Agach is higher than the 400 Bq/m³ action level for old houses. Owners should be advised to
ventilate their house and radon levels should be continuously monitored if no relocation is foreseen.

- The actual contamination of the river water is below the exemption limits for drinking water.
- Water should best be filtered since the sediments contain radionuclide concentrations higher than the exemption limits for soil.
- The locally provided drinking water in Mailuu Suu and surrounding villages is safe for human consumption (from a radiological aspect).
- Soil sampled at hot spots at tailings, surroundings of tailings and Kara Agach have radionuclide concentrations above the exemption limits. T3 T5, T7, T4 should certainly be fenced but also at other tailings trespassing by people and animals should be restricted.
- At Kara Agach soil samples measured exceeded the limits for uranium and radium with about a factor 20 for uranium and between 8 and ~ 1600 for radium. Cultivation of food crops and animal fodder should be prohibited at Kara Agach. Children should not play on these soils! At Mailuu Suu levels in soil are a factor 20 and much more lower than at Kara Agach.
- All vegetation and crops sampled on the tailings and in Kara Agach exceed the limits for alpha, uranium and radium! People living at Kara Agach should be advised not to use locally grown or reared food stuffs.
- Uranium concentrations in food collected at the Mailuu Suu market place and locally grown food were below the limits. Alpha concentrations in food were above the limit for human consumption when provenance was Kara Agach.

3.2 Radiological assessment for the actual condition

The releases of radionuclides from the tailings and waste rock deposits may give rise to exposure of the local population via different pathways. The exposure can take place directly via external irradiation and indirectly via inhalation of resuspended soil particles, radon, and ingestion of locally produced food products like vegetables, fruit, milk etc. In recognition of the fact that it is not possible to assess doses to each member of the population individually, the critical group concept\(^1\) was developed and is now widely adopted. For the Mailuu Suu region, a subsistence farmer community is used as representative for the habits of the critical exposed individuals. This is based on the assumption that subsistence farmers make a (reasonable) maximum use of local environmental resources. Age-dependent varations in metabolism are considered by calculating the individual dose to an adult and a child (< 15 years). A habit survey was conducted to investigate the dietary characteristics of the local community and to characterise how local environmental resources are exploited. These data were used to derive the characteristics of the critical group. To assess the dose impact on individuals of the critical group, a biosphere model was used. This model describes the transport of the radionuclides released into the biosphere, their transfer through the food chain and the subsequent exposure to humans.

External exposure and inhalation dose

The external exposure is around 1 mSv/a in Mailuu Suu and Kara Agach of which 0.8 mSv/a is due to background radiation

\(^{1}\)The group is representative of those individuals expected to receive the highest dose equivalents from the source of radiation under consideration (IAEA, Safety Series N° 57, 1982)
The radon exposure is around 5 mSv/a. in Mailuu Suu and Kara Agach. This is considered normal and is below the 7 mSv/a to which a person living in a house with 400 Bq/m³ (European action level) is exposed. If the radon concentration in the one house at Kara Agach built on the heap with very high radon concentrations would be included, the average radon exposure would be 10.5 mSv/a (Table ES-2)

Dust inhalation, even from the contaminated soil at Kara Agach (at Mailuu Suu soil contamination levels are about a factor 10-20 lower) is negligible (< 0.1 mSv/a)

Table ES-2: Predictions of the radon inhalation dose and external dose of critical group members (mSv/a)

<table>
<thead>
<tr>
<th>Place</th>
<th>Adult Inhalation of exhaled radon</th>
<th>External irradiation</th>
<th>Child (10 years) Inhalation of exhaled radon</th>
<th>External irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>indoor</td>
<td>outdoor</td>
<td>indoor</td>
<td>outdoor</td>
</tr>
<tr>
<td>Kara Agach</td>
<td>1.02E+01</td>
<td>3.01E-01</td>
<td>1.10E+00</td>
<td>1.22E-01</td>
</tr>
<tr>
<td>Mailuu Suu</td>
<td>4.69E+00</td>
<td>2.64E-01</td>
<td>1.04E+00</td>
<td>1.02E-01</td>
</tr>
</tbody>
</table>

Ingestion dose

It is very conservatively hypothesised that people living at Kara Agach consume locally produced food and consume water from the Mailuu Suu River. In fact people consume uncontaminated water (with respect to increased radioactivity) provided by the sediment collection bassin.

Most of the dose for people living at Kara Agach comes from the ingestion of contaminated food (> 10 mSv/a). A considerable decrease in ingestion dose could hence be obtained by consuming bought-in food. When consuming locally grown crops in Mailuu Suu town (factor 10-20 or lower soil contamination), the expected ingestion dose would be a comparable factor lower.

It is seen that the calculated doses for the current situation at Kara Agach are much higher than the dose limit of 1 mSv/a for members of the public. For an adult and child (of 10 years) of the critical group living at Kara Agach, a total dose of 22 mSv/a respectively 39 mSv/a was obtained (Table ES-3). The ingestion of drinking water contributes with less than 0.1 mSv/a to the total ingestion dose, the standard set by WHO.

Table ES-3: Calculated total dose (mSv/a) for the current situation at Kara Agach

<table>
<thead>
<tr>
<th></th>
<th>Inhalation dose</th>
<th>Ingestion dose</th>
<th>External dose</th>
<th>Total dose</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dust radon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adult</td>
<td>7.77E-02</td>
<td>1.05E+01</td>
<td>9.61E+00</td>
<td>2.14E+01</td>
</tr>
<tr>
<td>Child (10 years)</td>
<td>7.72E-02</td>
<td>8.21E+00</td>
<td>2.89E+01</td>
<td>3.86E+01</td>
</tr>
</tbody>
</table>

Looking at the Kara Agach situation, we see that the ingestion dose and inhalation dose of radon are the main pathways. Since more than 90 % of the ingestion dose is caused by the ingestion of locally cultivated food crops (as discussed above), we would recommend restricted use of these food crops. The dose due to inhalation of radon in indoor air can be reduced by increasing the ventilation rate in the houses and other protective actions which limit the radon flux from soil into the houses. Another necessary action would be to move people living in the one house with high indoor radon content.

The dose limit of 1 mSv/a is however not directly applicable to cleanup decisions, because its use could, in some cases, invoke the use of action that causes more harm than good, i.e. the action is not justified. ICRP 82 recommends the use of generic reference levels for cleanup, expressed in terms of existing annual dose. Since the average annual individual doses worldwide from natural sources vary from 2.4 to 10 mSv/a, an existing annual dose approaching about 10 mSv/a is chosen as generic reference level below which intervention is unlikely to be justifiable.
for prolonged exposure situations. Above an existing annual dose of 100 mSv/a intervention will almost always be justified. For an existing annual dose between 10 mSv/a and 100 mSv/a as obtained for Kara Agach, ICRP states that intervention may possibly be necessary and its justification should be considered on a case-by-case basis as appropriate.

Irrigation and seepage from Tailing 3

- People may use the river water for irrigation practices: this is actually not the case for people living in Mailuu Suu and villages nearby but people living downstream Mailuu Suu do so. The extra dose from irrigation with contaminated river water is negligible (< 0.1 mSv/a). It should be mentioned that actually people do not use river water for irrigation but water from the sediment collection basin.
- The extra dose due to seepage from tailing 3 is negligible (< 1 µSv/a)

4 Assessment of risks

4.1 Extent of radionuclide leaching from Tailing 3

Hydraulic modelling for Tailing 3 was performed by SCK-CEN in order to estimate the direction and magnitude of water flow under saturated and unsaturated conditions without taking into account potential inflow from uphill areas. Transport calculations were done for the four species decay chain $^{238}\text{U} => ^{234}\text{U} => ^{230}\text{Th} => ^{226}\text{Ra}$. The flow model assumes that groundwater velocities are vertically downward above the groundwater table, whereas below groundwater table a strong lateral component exists. At the seepage face, which is supposed to correspond with the interface with the nearby river, velocities are largest as all flow paths converge in a fairly small cross-sectional flow area.

Considering the available data on the radioactivity inventory and some dispersion relevant parameters, and considering an average annual Mailuu Suu river flow rate (9.1 m³/s) the hydraulic modelling estimated following concentration load in the Mailuu Suu River following leaching from Tailing 3 (Table ES.4.).

| Table ES-4 Calculated maximum concentration in Mailuu Suu river based on the first 10 000 years considering a river flow rate of 9.1 m³/s. |
|----------------------------------|----------|----------|----------|----------|----------|----------|----------|
|                                  | U-238    | U-234    | Th-230   | Ra-226   | Th-232   | Ra-228   | Th-228   |
| Max. concentration in river water (Bq/m³) | 2.1E-1   | 2.1E-1   | 1.0E-4   | 6.7E-4   | 2.1E-1   | 1.0E-4   | 6.7E-4   |
| Standards in Kyrgyzstan          | 21800    | 81400    | 8140     | 1998     |          |          |          |

It is clear that the expected additional concentrations in the river water following leaching from tailing 3 are far below the Kyrgyz limits for drinking water. As a result, there is probably no adverse effect on human health. The excess dose due to leaching from Tailing 3 is negligible (< 1 µSv/a).

Also for the heavy metals it was demonstrated that the estimated concentrations are much smaller than the guidelines values provided by the WHO or the drinking water standards given by EPA. As a result, there is probably no adverse effect on human health, based on the values found.

It is also concluded that the COLMIX-methodology (concrete columns) proposed for stabilizing the tailing material will not affect the leaching of radionuclides to a significant extent. The water stream will be directed around the columns and the flow-path-length may increase a bit but this will not affect the leaching.
4.2 Transport of radionuclides by the Mailuu Suu River in case of disaster and resulting radiation exposure

4.2.1 Radionuclide transport in case of disaster

A modelling study was carried out by SCK-CEN with the objective to evaluate how, how quickly and where the radioactive materials from the tailings would be transported by the Mailuu Suu River for three selected accidental scenarios.

- **Scenario 1**: a significant fraction (30%, 70% or 100%) of tailing no 3 is quickly poured into the river triggered by heavy rains leading to a landslide that would push the tailing materials into the river, or a failure of the tailing itself i.e. triggered by an earthquake.

- **Scenario 2**: a landslide blocks the river downstream of tailings 5 and 7 dam up a reservoir lake (volume between 1 and 2 millions m$^3$), the would extend to the base of tailings 5 and 7 which would partly fail into the reservoir waters. The contaminated waters would then be released after a quick or progressive failure of the obstruction.

- **Scenario 3**: in the case of a sudden failure of the natural dam as in the previous scenario, tailings 3, 8, 18, 21 and 22, located downstream of the dam could be taken into the river by the flood wave. Peak discharges in excess of 2000 m$^3$/s have been calculated for this scenario by JM Lejeune.

Considering the first scenario, a conservative average activity concentrations of alpha emitters of about 500 Bq/g for Tailing 3 and a sediment load of $C_s = 22$ kg/m$^3$, a conservative value of the alpha activity concentration in the river after an accident during the spring period can be as high as 11 Bq/ml, which renders the water unfit for consumption.

Such high levels of water contamination will probably not last more than a few days or weeks, but it is very difficult to predict how long it will take to reach acceptable levels again. In particular, since contaminated materials might be temporary trapped and might even be hidden by uncontaminated sediments until mobilised again during a subsequent flooding period, important increases of the contaminant concentration cannot be ruled out, even a long time after the accident itself.

The scenario of sudden failure of a natural dam, with discharge in excess of 2000 m$^3$/s is even more complex to tackle. With such a discharge, the river will have an enormous sediment transport capacity. Very high contaminated materials concentrations in the water will be possible during a short period of time. However, use of large amounts of this water at the time of such catastrophic but short event is unlikely as the population will have other motives of concern.

Detailed studies of flow and sediment transport for the selected disaster scenarios would be complex, would require a significant investment in data acquisition (numerical terrain model, tracer tests with marked sediments) and, given the current state of the knowledge on sediment transport in natural channels, would still only achieve very approximate predictions of the dispersion of the contaminated materials as a consequence of an inevitably stylised disaster scenario. Given that any disaster scenario is likely to have serious radiological consequence anyway, a better investment should be made on water quality monitoring equipment and emergency procedures, in addition to the prevention measures detailed elsewhere in this document.

4.2.2 Increased radiological exposure in case of disaster

Two scenarios were evaluated. The first scenario assumes that the waste material of tailing N° 3 will be evacuated by the river in a few days by considering a sediment load of 10 kg/m$^3$ water. In agreement with the first disaster scenario, the second scenario also assumes that tailing N° 3 is suddenly poured into the river and that the suspended matter only consists of the waste material.
from tailing No° 3. The only difference is that the current mean water flow and sediment load will be used to calculate the dose. According to this second scenario, it will take about two years before the waste material has been removed by the river. This scenario leads to the higher dose increment. It is assumed that the critical group will be exposed via the same exposure pathways as considered for the current situation.

Under scenario 2, the outbreak of the tailing 3 content to the Mailuu Suu River can lead to a considerable dose to the people living downstream Mailuu Suu since they use the river water for irrigation and drinking water purposes. Most of the ingestion dose comes from the ingestion of drinking water and consumption of fish, each accounting for 10 mSv/a for adults and respectively 25 and 9.5 mSv/a for children. Ingestion of contaminated food following irrigation accounts for 0.6 mSv/a for adults and 10 mSv/a for children. If the actual drinking water provision remains unchanged and people will be forced to use the contaminated water these are the likely doses to which people will be exposed to.

There are 5000 people living downstream Mailuu Suu in Kyrgyzstan, so the collective dose resulting from 2 years exposure may be considerable.

4.3 Landslides and mudflows

Recent field evidence namely in the area and upper vicinities of Tektonik and Ko-etash Landslides (observation of widening and coalescing extensional cracks, of subsiding blocks, and continuing and accelerating displacements recorded by extensometer measurement results) as well as the various historically observed river obstructions by landslides and recent re-activations (Tektonik-Landslide, May 12, 2002) do confirm that river obstruction is a sheer reality and not a hypothetical working assumption. Therefore, the so-called accidental scenario has a non-negligible probability of occurrence. The only debatable issues are the exact location, timing, and extent of probable future river obstructions and their consequences and stability with time.

Also, it must be realised that the river blockage itself, independently of the presence of the tailings, is a real hazard for the Mailuu Suu town.

Uphill to the E and SE towards the watershed the landslide source area for the Tektonik LS appears to be growing in extent above the main scarp with new cracks appearing and widening in the surficial cover deposits of loess like loam. The unstable soil masses are composed partly of loess-like loam, which consists of slightly sandy low plasticity silt, with high porosity but also of old landslide and debris slide - and rock fall deposits with large limestone blocks.

The head areas of Tectonic-LS below the main scarps exhibit a block and terrace morphology which is indicative for unstable slope conditions and a dynamic and extensional slope-regime. These features are also observed in the Northern part of the cliff faces surrounding Tp. No. 3, 9 and 10 like an amphitheatre.

According to Geopribor this mass of about 300000 to 400000 m³, confined in the upper edge in the south-east part of the landslide, appears particularly unstable and is crossed by a number of cracks. In case of failure, a small part of these masses (30000-40000 m³) may impact tailings n°3 and 9. Recent field observations and extensometer measurements document that the head and crown portion of the Tektonik LS are prone to repeated down slope displacements.). Also in this area, the so called “Shelf area of soil creep” with an associated talus-creep seem to be engaged in a slow creep like displacement directed towards tailings impoundment No 3 which could transform into a more rapid displacement and even unload under the appropriate conditions. (i.e. water saturation coupled with seismic effects). In this case the beach area of Tp. 3 could be impacted by an additional sediment load causing a further, - maybe detrimental -, reduction of its structural stability (Geopribor, 2002, Personal communications).
According to GESTER, the "cliff" dominating Tailing 3 and adjoining tailings, is generally uncovered, with surfaces having slightly lower slopes and containing thin surface deposits of material carried downhill. The cliff exhibits no sign of global instability. The most resistant sandstone benches from the Cretaceous have created small rocky overhangs that may detach.

Material has been transported on this cliff from the triangular extension south of the Tektonik landslide before tailing 3 was constructed. With respect to the lateral extension south of the Tektonik landslide, GESTER confers that in general there are signs of instability and reactivation of the Tektonik landslide.

4.4 Stability of tailings impoundment No. 3

Already several previous assessments have concluded that the physical stability of Tp. No.3 is critical due to the fact that the tailings body is highly saturated and constantly replenished with water and due to continuing accumulation of sediments on its beaches from cliff-face erosion. Because of this, part of the tailings deposits have been removed in ?1968.

Stability calculations (TALREN) carried out by GESTER based on laboratory tests on tailings material also demonstrate that the current situation is apparently at the state of limited stability.

With the value Cu = 25 + 2,6z deducted from the laboratory testing, the safety coefficient of the current situation is F = 0,96. The current situation is apparently at least at the state of limited stability, which is confirmed by the extensiometric measures undertaken by Geopribor; hence, we admit that, as a reference only, the actual safety coefficient is F = 1,00 which corresponds to the limit of equilibrium. This value of F=1.00 was used in each of the following case studies.

Taking into account the seismicity of the region the influence of accelerations induced horizontally and vertically by an earthquake inside the tailing was examined by GESTER:

Under pressure of an earthquake applying a pseudostatic acceleration (PSA) horizontal (see Table ES-7) of γh = 0,1 g (limit between 7 and 8 MSK) and a pseudostatic acceleration (PSA) vertical of γv = + or – 0,05g, the safety coefficient F is 0,71. Under the influence of a strong earthquake applying a pseudostatic horizontal acceleration of γh = 0,2 g (limit between 8 and 9 MSK) and a pseudostatic vertical acceleration of γv = + or – 0,1 g, the safety coefficient F falls down to 0,54.

4.5 Seismicity

In terms of tectonics, several active faults are reported in the area:

- the Talas Fergana fault
- the Mailuu Suu fault
- the Central Fault
- the fault underlying Tektonik Landslide as indicated by geophysical investigations

In terms of seismic events, reference is made to an earthquake with an intensity of 9 on Richter scale experienced in Andijan in 1902. A magnitude 6.2 earthquake has been observed (15/05/92) at about 35km from Mailuu Suu city. An earthquake of M=7.3 has been recorded on the other side of the Talas Fergana fault.

In a recent study the complete seismic data set for Kyrgyzstan was combined with information concerning tectonics and active faulting in order to define seismic zones over the country. For each zone Abdrakhmatov et al. (2002) calculated the magnitude for a recurrence period of 475 years that can be estimated by both the mean Gutenberg-Richter law and the upper 90% prediction limit (see Table ES 5). According to this map the Mailuu Suu area belongs to zone 16.
- Central Fergana Range with active Arslanbob fault. The associated peak ground accelerations is for the area of Mailuu Suu 0.25g to 0.30g.

**Table ES-5: Magnitude of seismic event**

<table>
<thead>
<tr>
<th>Zone n°</th>
<th>mean law a-value</th>
<th>upper90%-prediction law a-value</th>
<th>b-value</th>
<th>R</th>
<th>Mmax-mean law 475 years</th>
<th>Mmax-upper prediction law 475 years</th>
<th>Historical Magnitude Mmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>4.00</td>
<td>4.00</td>
<td>0.90</td>
<td>/</td>
<td>7.4</td>
<td>7.4</td>
<td>6.4</td>
</tr>
<tr>
<td>Zone 16</td>
<td>4.10</td>
<td>4.47</td>
<td>1.03</td>
<td>0.97</td>
<td>6.6</td>
<td>6.9</td>
<td>5.5</td>
</tr>
</tbody>
</table>

In another study the maximum peak ground acceleration at Mailuu Suu obtained with attenuation formula currently used in the Western practice of earthquake engineering (McGuirre, Cornell, Campbell, Joyner) ranged between 0.14 and 0.47 (Table ES-6)

**Table ES-6: An independent evaluation of Peak Ground Acceleration (PGA) at Mailuu Suu**

<table>
<thead>
<tr>
<th>Magnitude M</th>
<th>Distance km</th>
<th>Max Peak Ground Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>20</td>
<td>0.21g</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.17g</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0.14g</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>0.32g</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.25g</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0.21g</td>
</tr>
<tr>
<td>7.5</td>
<td>20</td>
<td>0.47g</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.37g</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0.31g</td>
</tr>
</tbody>
</table>

The peak ground accelerations associated to the accidental scenario and associated classical pseudostatic coefficients\(^2\) of slope stability calculations are given in Table ES-7.

**Table ES-7: Evaluation of Peak Ground Acceleration and pseudostatic coefficients for the various scenarios**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Peak Ground max. acceleration</th>
<th>Pseudostatic coefficient horizontal</th>
<th>Pseudostatic coefficient vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidental</td>
<td>0.25g</td>
<td>0.10g</td>
<td>0.04g</td>
</tr>
<tr>
<td>Catastrophic</td>
<td>0.35g</td>
<td>0.14g</td>
<td>0.07g</td>
</tr>
</tbody>
</table>

It is noted that based on consortium experience in liquefaction analysis of hydraulically deposited materials, in all tailings with high water table, total liquefaction of the tailings with spreading of the material in the river is certain under 0.25g peak ground acceleration (PGA). In tailings with gentle slope, local liquefaction is likely to be initiated under 0.15g PGA. Major displacements and beginning of general failure are to be expected at 0.20g PGA.

According to Kyrgyz construction norms and rules (CH – P 11-7-81) construction should allow for maximal amplitudes of vertical and horizontal accelerations in Kyrgyzstan equal and not less than 200 cm/s\(^2\) (0.2 g). From the tables above it is clear that even higher values for PGA can be expected. Abdurakhmatov et al. (2002) mentioned that for the design of the Toktogul dam a PGA value of 0.5g was required (10 % probability of exceedance in 100 years).

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\(^2\) Pseudo static coefficients for slope stability calculated from PGA following the French Standards (AFPS rules 1990). These coefficients are only valid if there is no liquefaction.
4.6 Probability of simultaneous occurrence of the triggering events

The accidental and catastrophic scenario imply the simultaneous occurrence of high rainfall period combined with strong earthquake shaking followed by after shocks. The probability of simultaneous occurrence of this scenario is far from being negligible: The key element in landslide activation is the piezometer level and the water infill in the existing tension cracks of the potentially unstable mass. The landslide records in the Mailuu Suu valley have also shown that earthquake activity was a triggering mechanism for slope instability.

In terms of comparison with flood, storm, or wave forecasts, the probability of occurrence of the accidental scenario is in the range 1/100 to 1/200 (return period 100 to 200 years). The probability of occurrence of the catastrophic scenario is in the range 1/500 to 1/1000 (return period 500 to 1000 years).

5 Evaluation of remedial options

Under this TACIS project various remedial options have been evaluated for tailing 3 including in situ stabilisation and tailing transfer to an alternative safer site.

5.1 In situ stabilisation of Tp. 3

Stability calculations of GESTER for various options using the TALREN-programme led to the conclusion that the actual stability of the tailings pond is low. Overloads or surcharges (additional material induced by hill erosion or landslides) accumulating on the top platform towards the cliff have a limited unfavourable effect. However, when additional deposition occurs close to the existing small (secondary) dam, the stability of the Tailing 3 is jeopardised.

These calculations demonstrate that the transfer of sediment load (and of the secondary dam) from this (central) area about 30m further uphill to the East has a positive (stabilizing) effect.

The new dam (2m high) will stop the erosion deposits originating from the slope above and an additional gutter along the dam will redirect the runoff waters towards the concrete gutter located at the south-west angle. A cover will limit water infiltration.

Also an additional embankment (cover or infill) located on the lower part of the downhill embankment of the tailing would have an extremely positive effect according to the GESTER calculations. On the other hand, an additional infill located on the upper part of the downhill embankment would have an extremely negative effect. A total cover should therefore not be applied on the entire downhill embankment but only on the bottom, except for a thin necessary cover to limit infiltration and radon release and erosion (geomembrane, clay, gabion) or after having removed part of the actual surface.

Very short term remedial measures

Accordingly reshaping and covering of the impoundment was therefore proposed by GESTER in the short term. These works can be rapidly executed using the logistics available regionally.

At the end of these first works, after erosion or the landslides have added an extra layer above the embankment, the safety coefficient $F$ becomes, for a 15 meter wide bottom embankment:

- In the absence of an earthquake: $F = 1.08$ (compared to the initial 1.00)
- During an earthquake creating PSA horizontal (pseudostatic horizontal acceleration:psa horizontal) $\gamma_H = 0.1g$ and PSA vertical (pseudostatic vertical acceleration:psa vertical) $\gamma_V = 0.05g : F = 0.87$
- During an earthquake creating PSA horizontal $\gamma_H = 0.2g$ and PSA vertical $\gamma_V = 0.1g : F = 0.63$

Mid term remedial measures
Hence, GESTER concludes that in the mid term an additional stabilisation is necessary for important earthquakes.

The creation of reinforcements using the COLMIX columns (incorporation of cement and lime by mixing using a triple bore) strengthened by metallic girders will considerably help increase the stability.

The safety coefficient in relation to a triple column density of 1 for 10 m², strengthened by 3 steel sections HEB 200, becomes for a 15 meter wide bottom embankment:

- In the absence of an earthquake: \( F = 1.33 \)
- During the earthquake’s PSA acceleration \( \gamma_H = 0.1g \) and \( \gamma_V = 0.05g \) : \( F = 0.96 \)
- During the earthquake’s PSA acceleration \( \gamma_H = 0.2g \) and \( \gamma_V = 0.1g \) : \( F = 0.67 \)

It is thus assessed by GESTER that with one triple column per 10 m², an earthquake of a pseudostatic horizontal acceleration of 0.1 g will not jeopardize tailing stability.

The expected cost of the COLMIX method is estimated by GESTER with approximately 2,13 Mio Euro. All costs were estimated from prices before taxes applied in 2002 in western countries, by companies working according to western standards and using suitable materials. Cost for dealing with radiation protection and control issues during the works are estimated at an additional 0.2 Mio Euro.

According to the intensity of the earthquakes which should be taken into account, the tightness of the column grid should be more or less modified. As technical and economic improvement, GESTER suggests to choose a density of 1 triple column every 7 m², strengthened by 3 steel sections HEB 100. Instead of treated and strengthened COLMIX columns, another solution with vibrated ballast columns could be analysed in order to avoid residues liquefaction.

Drainage of excess pore-waters inside the bulk of the “pulpa” could eventually improve its resistance, but the too fine tailing granulometry does not allow (too low permeability). There were cases were drainage of fines was performed (WISMUT tailings) by applying surface pressure on the tailings and extruding the water through vertical wicks. However, the limited stability of tailing 3 does not allow for increased surface pressure. Maybe drainage by electro-osmosis would work but earlier tests by Russians failed (personal communication Geopribor). Detailed preliminary studies are required to test the feasibility of this option.

Hydraulic modelling for T3 suggested no significant decreased leaching from T3 to the Mailuu Suu River following application of COLMIX columns.

The annual dose impact to workers when applying the COLMIX stabilisation method is lower than the annual dose limits of 50 mSv/a for workers and also lower than the weekly allowed doses of 1 mSv (Table ES 8).

### 5.2 Transfer of tailings to a safer site

It is understood that an earthquake has a direct adverse effect on tailing stability. Even the COLMIX improved tailings will fail in case of earthquakes with moderately high activity. The second possible adverse effect is that of a landslide or of soil creep accumulations from the escarpment cliffs east and above T3, which would create an overload or surcharge on the tailing and could provoke dam rupture. A concomitant effect, is the risk of a liquefaction of the residues which are water-saturated, due to constant water influx or infiltration.

Therefore, and for the long term the alternative option of transferring T3 and other tailings depositories to a safer site has to be discussed and was investigated further.

It must be understood that the complexity of a tailings transfer with all the long term warranties, or the difficulty in extracting the radioactive residues most probably in form of a paste or mud (“pulpa”) should not be underestimated. Transport conditions around the northern city limits of
Mailuu Suu must be adapted to this task, be safe enough and include appropriate measures for (radio)-protection of the population and workforce. Water treatment capacity must be installed and operate for several years. The selected alternative site must be thoroughly investigated and prepared and constructed along the guidelines of a disposal cell concept.

Hence, such relocation can not be accomplished before several years, since detailed pilot studies of the new tailings disposal site and a full fledged feasibility study still have to be prepared. Moreover it has to be realised that on top of providing appropriate transport conditions and important investment funds, adequate technologies, machinery, materials and personnel are still not yet fully available in Kyrgyzstan.

Under these circumstances it is important to start with the necessary short term stabilisation measures immediately or as soon as possible regardless of the outcome of the feasibility study and the final decision.

After pre-screening several sites proposed by Kyrgyzstan authorities, the location of Tailing 15 was selected for preliminary investigations including drilling a number of boreholes and examining the borehole samples. The ~15-km road is actually in poor condition. The advantages of this site are that transport does not pass through the city of Mailuu Suu or through other populated areas and that the site has sufficient free space next to tailing 15 to store tailing 3 plus additional residues. The disadvantage is access to tailing 15: the road must be improved if not reconstructed entirely. It was decided jointly with Kyrgyzstan authorities that if waste from tailing 3 is to be transferred, the new depository will be built alongside tailing 15.

According to an assessment by GESTER, the new storage site or depository for tailings T3 will be located in a depression next to tailing No. 15. It will be excavated in the upstream side of the valley and will be surrounded by dykes downstream. Other deposits could subsequently be transferred to the No. 15 site, e.g. T 7. In this case, the thick loess cover of and the already deposited tailings T15 will have to be excavated and temporarily stored in another area nearby. These deposits will be separated in hydraulically independent compartments by small dykes installed at the bottom. Several cells will have to be constructed at the disposal site. The bottom and sides of each cell and of the entire impoundment will have to be sealed in accordance with the so-called disposal cell concept and equipped with a proper cover design used in the western world for uranium tailings.

A hydrological modelling of the new disposal suggested that by addition of one or more impermeable layers in the cover design, the water flux through the cap may be easily reduced to 1% of the net rainfall. Also addition of sorptive material to the bottom layer will significantly retard leaching.

5.2.1 Excavation and transport of the tailings

Due to the water saturated consistency ("pulpa") of processing residues stored in tailing No. 3, excavation will have to be done with a dragline or large cableway excavator, in order to avoid machines moving on top of the excavated material. The waste will partially drain on the edge of the tailing before being loaded. Transport will be in reinforced sealed containers, with sealed locked covers. The containers will be loaded aboard trucks that cannot drive on waste in the new deposit for unloading. These containers will be unloaded and emptied in the deposit by a cable device (sort of cable lift) or a crane with a large boom.

Drained waters will have to be collected in a sealed reservoir and water treatment capacities have to be installed.

For the transfer of any drier tailings from other depositories, excavation and transport conditions are less difficult. This excavation can be done traditionally. Transport could be by dump trucks equipped with sealed and locked bodies.
When unloading, however, trucks cannot always drive on top of waste. In this case again, a crane with a large boom will be used to transfer the contents of trucks to the storage compartments.

5.2.2 Estimation of transfer costs

Costs were estimated by GESTER with about 3 million Euro for the transfer of Tailing 3 (80000m³) and 23 million Euro for the transfer of tailings T3, T5, T7 and T8 (880,000 m³) on the basis of prices before taxes applied in 2002 in western countries, by companies working according to western standards and using suitable materials.

Costs for radiological monitoring and radiation protection during the transfer of Tailing 3 works are estimated at 0.35 Mio Euro. Costs for continued monitoring after transfer of the Tailing are roughly estimated at 0.02 Mio Euro/year.

The costs presented however do not include investments for the potential water treatment installations nor potential costs with the disposal of contaminated trucks and other machinery. The tailings relocation costs estimated above may hence increase.

Preliminary cost estimates were provided in the World Bank report for the option Tailings relocation (based on the report by Clifton & Associates), including emergency works for landslides hazard mitigation (2.5 Mio USD) as follows: approximately 21.7 Mio USD. These costs are expected to be seriously underestimated since costs refer to local market conditions.

5.2.3 Workforce exposure during transport of Tailing 3

For the discussion of the dose impact to workers, Western conditions are considered.

It is assumed that the relocation of tailing N° 3 and the construction of the new disposal site at T15 will take 18 months of work.

It is seen that the annual doses are lower than the annual dose limits of 50 mSv/a for workers and with exception of the loading of the containers, they are also lower than the weekly allowed doses of 1 mSv (Kyrgyz Norms, Mr. Mombetov, personal communications) (Table ES 8).

Table ES-8: Individual dose to the workers

<table>
<thead>
<tr>
<th>Total work hours</th>
<th>Dose (mSv)</th>
<th>Annual dose (mSv/y)</th>
<th>Dose per week (mSv/week)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total dose</td>
<td>External dose</td>
<td>Inhalation dose</td>
</tr>
<tr>
<td>Translocation of tailing 3</td>
<td>3520</td>
<td>6.16E+01</td>
<td>1.98E+01</td>
</tr>
<tr>
<td>Loading of containers</td>
<td>1170</td>
<td>2.05E+01</td>
<td>6.05E+00</td>
</tr>
<tr>
<td>Transportation of material</td>
<td>3520</td>
<td>5.45E+01</td>
<td>1.61E+01</td>
</tr>
<tr>
<td>Creation of new disposal site</td>
<td>1360</td>
<td>2.17E+01</td>
<td>6.39E+00</td>
</tr>
</tbody>
</table>

5.2.4 Radiological evaluation of new waste disposal site

Leaching of radionuclides to ground water

It is assumed that the processing residues with the highest activity will be disposed of at the bottom of the repository and that the waste material will be isolated from the geosphere and biosphere by geotechnically selected materials to the extent that the water flux through the cap may be easily reduced to 1% of the net rainfall. Maximum concentrations in the groundwater are reached after 50-100 years for most radionuclides and remain nearly unchanged during at least several hundred of years.

The expected concentrations in the groundwater below the new disposal site at T15 are much higher than the expected concentrations resulting from leaching to the Mailuu Suu river. This is partially due to less leaching (barriers) and partially as a consequence of the much lower groundwater flow compared to the Mailuu Suu river flow rate (less dilution). Except for Ra-226,
the expected concentrations in the groundwater are lower than the drinking water limit in Kyrgyzstan (Table ES-9). In the very unlikely event that groundwater would be used for drinking water at the T15 location, this should be prohibited.

**Table ES-9: Calculated concentrations in the groundwater below the new T3 disposal site.**

<table>
<thead>
<tr>
<th></th>
<th>U-238</th>
<th>U-234</th>
<th>Th-230</th>
<th>Ra-226</th>
<th>Th-232</th>
<th>Ra-228</th>
<th>Th-228</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. concentration in river water (Bq/m³)</td>
<td>8000</td>
<td>8000</td>
<td>1000</td>
<td>6300</td>
<td>5.5E+2</td>
<td>3.6E+3</td>
<td>1.7E+3</td>
</tr>
<tr>
<td>Standards in Kyrgyzstan (Bq/m³)</td>
<td>21800</td>
<td>81400</td>
<td>8140</td>
<td>1998</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These results are obtained for a pessimistic scenario of a relatively high $K_s$ value of $10^{-7}$ m/s. When $K_s$ is $10^{-9}$ m/s or smaller by addition of one or more impermeable layers, the water flux through the cap may be easily reduced to 1% of the net rainfall. Addition of sorptive material will significantly retard leaching. As a result, the maximum fluxes will appear at a much later time.

### 5.3 Landslide stabilisation

Transfer of the tailings does not solve fully the Mailuu Suu public safety issue due to river blockages caused by the unloading of landslides or unstable slopes and related inundation in a catastrophic scenario. Therefore the option of landslide stabilisation has to be considered among other options.

In a recent World Bank experts report (March 2002) several suggestions have been made to try to stabilize the critical slope areas menacing the tailings depositories either directly or indirectly in the Mailuu Suu river valley. The preliminary cost estimate of the World Bank for landslide stabilization for Koe-Tash and Tektonik Landslides including limited tailings remediation works amounts 24.4 Mio USD. These suggestions have been examined and assessed as outlined below.

**Koi Tash landslide**

Due to the volume of the Koi Tash landslide (estimated volume of unstable material is 5 million m³), to the thickness of the sliding mass (average 15m and 40 m at maximum), and to the severe earthquake conditions prevailing in the area, GESTER does not believe that the solutions presented by the Bank could be successful to stabilise the landslide under static and dynamic loading conditions.

**Tektonik landslide**

The Bank considers that the slide could be stabilised with simple methods: deep drainage trenches, vertical shafts with radial drains, reshaping of the slope, small diameter wells.

Also in this case GESTER does not concur with the World Bank report of March 2002 and considers that the Tektonik landslide cannot be effectively stabilised for static and earthquake loading conditions with a reasonable cost effective civil engineering solution. The reasons are the type of landslide and the volume of the unstable soil mass. The landslide combines superficial mudflows on rather steep slope and mass movement. There is nearly no method to stabilise mudflows. The classical practice in Europe in mountain roads is to channel the mudflow above reinforced concrete structure. The only method to try stabilising the deep mass movement is drainage. The design of such a system would need a thorough investigation (boreholes, piezometers and inclinometers) to fully understand the deep sliding mechanism and the hydrogeological situation. In addition, the drainage system should not be sheared off by the slide. The drainage work will be a huge undertaking calling for a system of radial drains drilled from a main drainage gallery (wells from the surface will be destroyed). In addition, this system will be totally ineffective for the mudflow component of the slide.
GESTER also believes that given the size of this landslide, it is beyond human capacity to improve or stabilise the landslide.

Other experts (i.e. World Bank report of March 2002) have proposed stabilization by draining the Tektonik landslide, either with vertical drains drilled from the surface, or with sub-horizontal drains drilled from a gallery passing under the landslide. GESTER believes that both techniques are totally unrealistic. For example, vertical drilling of a 0.30 m diameter wells would require machines that cannot be installed on the major part of the landslide surface. In addition, each drilling rig should be equipped with an electric-powered submersible pump and with an evacuation tube leading down to the river. In a landslide with such a brutal activity, these wells would be sheared off and their junctions cut, possibly even before they start operating. The other solution (sub-horizontal drains) involves the creation of a gallery in the substratum under the landslide. However, this would be extremely difficult since the substratum contains a major fault. Sub-horizontal wells would also be sheared off, probably before becoming operational.

Isolite Landslide

The Bank does not propose any method to stabilise the landslide (Relocation of Isolite plant is being considered). The Consortium considers that the landslide cannot be economically and successfully stabilised.

In conclusion the consortium considers that the classical landslide stabilisation solutions suggested by the World Bank will not be successful to stabilise the Tectonic and Koi Tash landslides in static and earthquake loading conditions. The technical feasibility of these actions is doubtful within a competitive budget. The consortium considers as well that the Isolite landslide cannot be stabilised economically. It is therefore proposed to find a solution to avoid the river blockage following a major landslide.

5.4 Solutions to avoid river blockage (Mailuu Suu river diversion tunnel or river-channelling)

These options and their variants attempt the complete isolation of the tailings from the major transport vector which is the Mailuu Suu River realizing that the landslides, independently of the presence of the tailings, are a real hazard for the Mailuu Suu town public safety.

A summary of the remedial solutions to avoid river blockage by projecting a Mailuu Suu River diversion tunnel or a river channelling is given in Table ES-10.

A solution may consist in channelling the river (even at maximum flow) through pre-cast concrete tubes or through covered concrete channels which would be able to support the eventually accumulating sliding masses above and keep the river in free flow.

It follows from Table ES-10 that solution D (channelling the river) offers the lowest cost. Unfortunately the feasibility of the solution is not proven (excavation of very stoney and wide river bed of a torrent) and the risk of landslide reactivation during the operation is a real hazard.
Table ES-10. Remedial options proposed to avoid river blockage.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Cost Mio US$</th>
<th>Main Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Long diversion tunnel LB</td>
<td>23.510 Mio US$ +5.329 Mio US$</td>
<td>28.839 Mio US$&lt;br&gt;Should be combined to channelling of Kara Agach river to fully achieve the public safety objective (5.329 Mio US$ included in the cost estimate). Some risk of reactivation of Tectonic landslide during this sequence of the works. Location of main fault and potential fault displacements (if active) to be clarified. Location of mining galleries and shafts to be clarified.</td>
</tr>
<tr>
<td>B. Long diversion tunnel RB</td>
<td>27.759 Mio US$</td>
<td>Fully achieve the objective in terms of public safety. Location of main fault and potential fault displacements (if active) to be clarified. Location of Mining galleries and shafts to be clarified.</td>
</tr>
<tr>
<td>C. Short diversion tunnels RB</td>
<td>21.392 Mio US$</td>
<td>Due to the constraints for locating the portals, the tunnels cannot be short (unless T5 and T7 are relocated). Final solution equivalent to the long RB tunnel (Solution D).</td>
</tr>
</tbody>
</table>

The long diversion tunnel solutions (Solutions A and B) do achieve the public safety objective of decreasing almost fully the dispersion of radionuclides and heavy metals by the water flow. Solution A (Left Bank) is slightly more expensive and presents some risks of landslide reactivation when installing concrete elements to channel Kara Agach river (another potential contaminant transporter) flow in front of Tektonic Landslide. Therefore the best solution as considered by GESTER at the present state of knowledge appears to be solution B, the long diversion tunnel in the Right Bank which allows coping easily with the Kara Agach River.

GESTER believes that the crossing of active faults by the proposed tunnel (solutions A and B) does not impede the feasibility of the tunnel solution. Should there be evidence of recent activity of the Mailuu Suu fault, then engineering solutions could be designed to cross the fault. These solutions can be the combination of a larger chamber (say 8m diameter supported with flexible rock support solution) with the main river tunnel crossing the fault on a bridge inside the chamber. The tunnel in these critical sections could be a steel articulated penstock. The budget given in the present report allows coping with this type of situation along a few decametres. Local tunnel design adaptations will also be necessary if the tunnel crosses the area of underground mine workings. Due to these and the geological features, the tunnel should be excavated with classical drill and blast technique (and not with a full face tunnelling machine).

In this assessment costs estimated by GESTER for the tunnel construction (without slides hazard mitigation and limited tailings remediation work) are close to 28 Mio Euro. These costs include design, construction (Mailuu Suu river diversion) and supervision (periodic inspections and fulfilment of public safety objectives).

It should be mentioned that resolving the problem of a possible river obstruction will not fully solve the problem for the people at Mailuu Suu. Imagine that by the impact of a landslide or an earthquake part of Tailing 3 is taken to the original Mailuu Suu River valley. People living nearby may be exposed to the tailing material by increased inhalation dose from contaminated dust and radon.

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3 Risks are not as important as with solution D (reduced width of the concrete elements and necessary excavations).
5.5 Proposed option: phased approach considering a combination of techniques

As outlined above, potential impact or indirect effect on some of the radioactive waste depositories deposits in the Mailuu Suu river valley (namely of Tailings 3, 5, 7, 8, 9, 10, 18, 19, 20 and 21) by seismic and/or slope- or structural instability - risks cannot be excluded. Historically this has been the case for tailings depository No.17 which was impacted by Tectonic Landslide in 1992. For this reason remediation options have to be selected that address the so-called accidental or catastrophic scenario as a non-negligible probability of occurrence.

Seismic hazards triggering slope instability and potentially loss of structural stability of waste deposits and associated repetition of river blockage events have to be classified as likely in the mid term and long term based on historical and even recent observations. Very little can be done against slope movements and seismicity in the critical sections of the Mailuu Suu river valley. Therefore access restrictions, monitoring, emergency preparedness measures and structural or physical stabilisation of impoundments that have to be considered as unstable in their present condition (i.e. Tailing 3) can only have short to mid term significance but are nonetheless necessary.

Under present project, considering the project objectives, the Consortium focussed its attention on Tailing pond 3.

In the very short term it is proposed to proceed with the fencing of the tailings of concern (Tailings 3, 5, 4, 7 and 13), put on warning signs on all other tailings awaiting fencing, and perform the minimal maintenance work (repair and cleaning of gutters, damaged dams, etc…) and monitoring. Additionally to execute fully the short term stabilisation works on Tailing 3 as proposed in Chapter 4.4.1 (Reinforcement of foot of tailing and displacement of upper dike with 20 m with a resulting increased stability of 40 %). Even if these short term remedial options will not guarantee tailing stability following an earthquake of moderate intensity, they are required given the actual limited stability of the tailing.

Since an additional stabilisation is necessary for important earthquakes, it is proposed to stabilise the tailing 3 downhill embankment using COLMIX treated columns in the short-mid term. It can be decided by the responsible authorities that these stabilisations are sufficient for the reasonable foreseeable impediments. Under the consideration, due to extreme caution, that catastrophic conditions could bring down (part of) Tailing 3 to the Mailuu Suu River, it may be decided to relocate the tailing. Such a translocation cannot be accomplished before several years since detailed pilot studies of the new tailing still have to be prepared. On top of that the transport conditions, the important investment funds, the meeting regarding available material, equipment and personnel which are still not fully available in Kyrgyzstan. It then becomes important to start the first stabilisation measures presented as soon as possible. These first stabilisation works should also be accompanied by a suitable drainage system and cover.

For all the other tailings the actual stability should be investigated, possibly following the method applied for Tailing 3. It should be decided if the actual stability is adequate or if it should be improved and if the improved stability is acceptable.

In the mid-term, also the replacement of the existing route is foreseen.

For the long term, and following the evaluation of a number of remedial options, two options are retained

- Excavation and transfer (first of T3 (110000) then , T5 , T7 and T8 (800000 m3) to an alternative safer site which could be Tailings depository No. 15 (at 15 to 20 km distance) pending more detailed investigations which are necessary and beyond the scope of this Tacis project.
- Diversion of the Mailuu Suu river by the long diversion tunnel in the right Mailuu Suu river Bank which allows also to cope easily with the Kara Agach River
Both options could only be outlined to some extent within the framework of this project and require an even more detailed site investigation, detailed feasibility study and project design before a final decision can be formulated. Obvious drawbacks or obstacles to be overcome for both options are summarised below.

**Option: Excavation and transfer of a selected number of tailings**

**Advantages**
- Removal of radioactive sources. Almost annihilation of the potential of dispersal of radioactivity.
- High public assurance

**Potential disadvantages or problems**
- Difficulty in extracting the radioactive residues most probably as a mud (probably only applying for Tailing 3)
- Radiological and environmental impact of tailings transfer and potential public disturbance (therefore sealed trucks required)
- Environmental suitability and sustainability of new site
- Additional costs related to necessary radiological surveillance and radioprotection measures during and after operation and clean up and also related to the necessary water collection and treatment facilities and post project monitoring.
- The relocation of the tailings does not solve fully the Mailuu Suu town public safety issue due to inundation in case of catastrophic scenario.

**Option: Right bank diversion tunnel**

**Advantages**
- The area will become a nearly dry sanctuary in which tailings are isolated without any adverse river influence.
- Stop of dispersive action of river

**Potential disadvantages and problems**
- Knowledge of exact location of old mine workings
- Tunnelling in unstable terrain (faults, young fractures, neo-tectonics, seismicity and related phenomena) could be problematic by itself and ultimately be capable to trigger mass movement all by itself.
  
  Especially the tunnel portal entering the hillside beneath unstable slope sections would have to be reason for serious concern. Undermining of the slope by the tunnel with consequent disturbance to the overlying rocks and soils and depression of the water table can lead to instability problems
- Proper maintenance and regular surveillance of the tunnel section and related costs.
- Potential tunnel blocking
- A tailing dump taken to the ‘former’ Mailuu Suu river valley, may lead to an increased exposure of the population due to increased radiation exposure.

According to the multi-staged approach proposed (Option 6 in section 5.1.) while continuing improving the physical stability of T3, monitoring, preparing emergency preparedness measures and establishing access restrictions and identifying population transfer zones in the short term, simultaneously start in the short and short-mid term with a mid-long term perspective assessing the feasibilities of both options, the translocation of the tailings and the long diversion tunnel in the right bank, based on additional information gathering. Options should be evaluated in terms of technical feasibility, health and environmental impact, economic costs and public acceptance...
until a decision can be made to choose between the two alternatives which will be projected subsequently.

5.6 Decision making

The landslides, independently of the presence of the tailings, are a real hazard for the Mailuu Suu town public safety. In a Western Europe financial and institutional context, with the pressure of public opinion for the no human loss concept in public safety, the risk of river blockage followed by the temporary dam failure risk would definitely lead to make decision in favour of a river diversion tunnel. A recent example from the French Alps is quoted in Chapter 4.2 (it is important to note that the threatened city had 500000 inhabitants). In Europe, diversion (or connecting) tunnels are also used in dams reservoir engineering where rock avalanche could isolate parts of the reservoir leading to uncontrolled blocked reservoir sections.

The tailings, when (slightly) impacted, independently of the presence of the landslides, are a potential hazard for the inhabitants of Mailuu Suu and people living downstream. In United States an example can be quoted where a uranium tailings or waste pile was transferred out of valley to prevent its loss of stability in case of flooding and then stored in disposal cell concept impoundment higher up topographically and several km away from the danger zone. This demonstrates that decision making is very much subject to the socio-economic, socio-political and cultural context.

Decisions on the introduction of remedial measures for long-lasting exposure situations can often be limited to considerations of whether or not any of the possible remedial actions will result in a net benefit. If so, the optimum measure can be taken as the one having the largest net benefit. In reaching such decisions it is important to consider carefully the benefits and disadvantages because some remedial actions can significantly disrupt the exposed population. Several factors (attributes, accounts) have to be considered in the selection of an optimum remediation strategy, e.g. effectiveness of the remediation with respect to dose reduction, monetary and social costs, impact on the environment, acceptability of the public, personnel safety etc. For the reasons stated above decision making in particular relies on close integration and cooperation between Kyrgyz authorities, experts and the local community. Comments of and discussions with all stakeholders and involved parties must be taken into account in a systematic way.

5.7 Proposed future work

Apart from short term (and required continued) actions to restrict access to tailing, for tailing maintenance, minimal monitoring, apart from the short term to mid term stabilisation work as proposed for T3, activities to assess the feasibility of the long-term remedial options preferentially proposed for further investigation (the Excavation and transfer of a selected number of tailings and the right bank diversion tunnel) should start simultaneously until a decision crystallizes on the preferred option.

During the initial phase of the the feasibility study, activities (pilot testing) regarding landslides hazard mitigation should be more or less simultaneous with the activities on the tailing deposits in order to further assess their physical conditions. This should be carried on until reaching the required level of knowledge for a selection of the preferred remedial option. Also it is important during this study to complement and maintain the system and strategic locations for an environmental monitoring network along the conceptual contaminant pathways from source to receptor.

An emergency preperardness plan should be developed and established.

Since we propose a phased remediation approach, additional information has to be collected and additional investigations have to be performed at different levels.
Generally, the actual situation should be more comprehensively recorded. Due to budget constraints, only rather limited environmental monitoring could be performed. Information should be gathered to have a clear idea of the reference conditions, the environmental base line conditions with which the remedial actions should be compared. The majority of these requirements are summed up below.

In the phased approach we also proposed to (temporarily) stabilise the tailing 3 with the COLMIX method. Most important complementary studies and field investigations required are the following:

- More detailed geotechnical and geophysical investigations of tailing 3
- Inertion tests to assess the increased mechanical resistance after the application of COLMIX
- Assessment of tailing stability with impacting factors and after COLMIX application
- More detailed radionuclide and other contaminants content of tailings for radiological and environmental assessment and to assess hazard to workers

_Design activities_

- Refine the proposed design and elaborate a complete workplan
- Assess need for sediment collection basin and dimension and cost plant if deemed required
- Detailed radiation protection guidance and programme during execution of works and radiation and environmental monitoring
- Post-project radiation and environment monitoring programme
- Costing

For the option: transfer of selected tailings to a safer site, complementary studies and field investigations required are the following:

- Geotechnical and geophysical investigations of tailings considered for relocation and the new disposal area (borings and tests)
- Geological and structural survey of the new disposal site
- Topography survey of new disposal site
- Assessment of actual tailing stability (with impact of landslide/earthquake/suction power of quickly emptying lake following river blockage dam break)
- Radionuclide and other contaminants content of tailings
- Environmental baseline study
- Dispersion relevant parameters for tailing materials/bedrock/sediment covers/bedrock
- Hydrological and hydrogeological information of tailings and new disposal site
- Radiological assessments
- Environmental hazard assessments
- Actual road characteristics

_Design activities_ to be performed in the next step of the project should:

- Detailed work programme and performance for loading at each specific tailing and unloading of tailings at new disposal site
- Detailed road improvement plan or road construction works
• Investigation (and design) of potentially other transport mechanisms
• Refine the proposed disposal design and adapt the detailed siting to the amount of tailing material that has to be allocated at the site.
• Assess need for sediment collection basin and dimension and cost plant if deemed required
• Detailed radiation protection guidance and programme during execution of works and radiation and environmental monitoring
• Post-project radiation and environment monitoring programme

For option the option: long diversion tunnel RB the complementary analysis of existing documents supplemented by complementary studies and field investigations should bring clear answer and design parameters on the following aspects:

• Precise localisation of old mining works
• Detailed topographical survey especially portal areas and Kara Agach River valley.
• Geological cross section along tunnel route.
• Precise localisation of the Mailuu Suu fault. Diagnosis on fault activity and evaluation of possible displacements (average yearly displacement and estimated one in case of earthquake of various magnitudes (especially for the design basis earthquake – DBE- and maximum credible earthquake- MCE).
• Peak ground acceleration for various earthquake return periods (following western approach: tectonic analysis + statistical analysis of observed earthquake events).
• Final evaluation of the Mailuu Suu and Kara Agach rivers floods for various return periods (and especially the 1/100 year flood).
• Stability of slopes in tunnel portal areas.
• Environmental base line study, radiological and environmental risk assessment

About 4 to 5 boreholes (with measurement of piezometer levels, water testing and sampling at tunnel level) should be drilled on the tunnel route. The location of the boreholes will be determined after the preliminary geological desk studies to confirm or amend the preliminary geological interpretation and adjust if necessary the tunnel route.

Note: In case a more detailed evaluation of inundation levels in Mailuu Suu town in the catastrophic scenario would be required, then a complete Dam Break analysis should be performed (with accurate topographical sections).

Design activities to be performed in the next step of the project should:

• Adapt the tunnel route to the geology,
• Finalise the hydraulic sizing of the tunnel,
• Detail the engineering solutions for the crossing of faults and mining galleries,
• Give the recommended location for Kara Agach incline,
• Make a zoning of the tunnel route in terms of internationally accepted rock mass quality ratings (Bienawski RMR5 or Hoek and Brown GSI6 or Barton Q system) with associated solutions for temporary rock support (before concrete lining),

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4 For Tunnel construction, there will be international bidding. The geological information should be provided to tenderers in an internationally accepted system.
• Design the tunnel intake and outlet structure,
• Finalise the route of the permanent road
• End up with a cost estimate including a revised evaluation of the unforeseen and contingencies,
• Give the preliminary construction program.

Assessment of the radiological consequences of a disaster scenario requires important additional information

For the evaluation of the potential total sediment load of a river
• hydraulic characteristics of the river such as the discharge, the depth, the shape of the wetted cross-section and the longitudinal bed slope
• characteristics of the sediments, such as the granulometric curve as coarse sediments are not so easily transported as fine sediments are.

For the disaster scenarios of a landslide blocking the Mailuu Suu river downstream T5 and 7:
• topography of the river bed and borders upstream the natural dam and the river flow in order to calculate volume of the lake formed and the level to which the tailing is inundated
• information on the stability of Taling 5 and 7 (impacted by lake) or tailings 3, 8, 18, 21 and 22 (potentially impacted by flood wave) should be available to predict if the tailing dams would erupt yes or no
• content of the radionuclides in the tailings for predicting the concentration of radioactivity in the river if the tailing dam would fail
• content of the radionuclides in the tailings and tailing granulometry to predict the amount of radioactivity leached from the tailings to the lake water and hence to the river after the natural dam rupture

In addition to the detailed investigation of options C and F as mentioned above and the additional information required for assessing the radiological exposure in case of a disaster scenario, one should engage in
• a thorough risk characterisation
• an assessment of the averted risk by the option
• a thorough radiological assessment
• a thorough environmental hazard assessment
• a study on the economic and socio-political implications of the remedial options, including the do nothing option and considering the risk factor (accident and disaster)

Local stakeholders, already included in all former steps, should then be invited to assist in the selection of the optimal remedial approach by Cost Benefit Analysis or Multi Attribute Utility Analysis, or other optimization technique.

\[5\] Rock Mass Rating (Bienawski)
\[6\] GSI: Geological Strength Index (Hoek and Brown)