UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

ATOMIC SAFETY AND LICENSING BOARD

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Hearing Exhibit

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Exhibit Title: Charlwood, "A Review of Alkali Aggregate Reaction in Hydro Plants and Dams," 1 Int'l Journal on Hydropower & Dams 3, 73-80 (May 1994)

A review of alkali aggregate reaction in hydro plants and dams

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Alkali-aggregate reaction (AAR) has become increasingly frequent in the concrete of hydro plants and dams around the world. The phenomenon was first identified in the 1930s, and tests and design standards were introduced in the 1940s to deal with it. However, because of the long life and large size of many hydraulic structures and the still incomplete understanding of the phenomenon, various types of reaction are still occurring, affecting plant and spillway operation and dam safety.

Concrete alkali-aggragate reactions in hydraulic plants and dams was the subject of an international conference held in late 1992 in Canada [Canadian Electrical Association, 1992[1]]. In a general review paper [Charlwood, Steele, Solymar and Curtis, 1992[2]] 78 cases of AAR in existing hydro powerhouses and dams were identified. Subsequent papers provided case histories at plants in Canada, Brazil, Pakistan, Zimbabwe/Zambia, USA, France and the UK. The objectives of this paper are:

- to analyse the nature and extent of the problem;
- to review case histories at the hydro plants and dams which were discussed at the CEA Conference with updated information where available;
- to look at available strategies and design options for remedial measures;
- to review the state-of-the-art of instrumentation and modelling; and,
- to present conclusions on the success of actions taken and identify potential developments for the future.

1. Nature and extent of the problem

The reactions occur between certain aggregates and alkalis in the cement content of the concrete, leading to the production of silica gels which then absorb water and expand, causing micro-cracking of the concrete and structural deformations. The reaction usually becomes apparent after about five to ten years, and may continue for 50 years or more. The micro-cracking can lead to loss of tensile and shear strength of the concrete, although compressive strength may be retained. The expansion will typically cause structural movements of several centimetres and can also lead to structural cracking of mass concrete and construction joints. These effects can cause leakage and loss of gate clearances, and distortion of the concrete supporting turbines and generators, resulting in the need for realignment and other measures to maintain the generator air gap, turbine runner and gate clearances.

Three types of AAR have been identified:

- alkali-silica reaction (ASR), which is associated with the formation of an expansive silica gel around the aggregate particles, and has been the most common form of AAR observed since the 1930s;
- slow/late expanding alkali-silicate/silica reaction (ASSR), which is associated with the expansion of coarse aggregate particles in addition to gel formation, and has only received attention recently; and,
- alkali-carbonate reaction (ACR), which is caused by the expansion of coarse aggregate particles containing argillaceous dolomitic limestones, and is less frequent than the other types of AAR. The exact mechanism of this type of reaction is not known.

The Table lists the known cases sorted by reaction type, aggregate and decade of construction.

The occurrence of AAR is also dependent on the alkali content of the cement. The alkali content is usually measured as the equivalent sodium oxide. It has been suggested that if the alkali content is less than 0.6 per cent, then AAR is unlikely to occur. However, such a criterion is not reliable, and should only be used as a general indication of the relative level of alkalis. Decisions on cement and aggregates in new structures should be based on testing.

Standard testing methods for checking for AAR susceptibility in new concrete involving mortar bars and concrete prisms have been found to work only for certain aggregates and not to give reliable information for others. This is partly because of the slow/late reaction, and partly as a result of the need for tight criteria which would represent the potential for damage in very large structures over long periods of time. New accelerated testing procedures involving tests in high alkaline solutions and at high temperatures (38 °C and above) are being calibrated using tighter criteria to address these requirements [Berube, Dupont, Pigeon and Stoian, 1992[3]; Grattan-Bellew and Danay, 1992[4]).

Mineral admixtures, pozzolans, have been used successfully as a replacement for Portland cement. These include ground granulated blast furnace slag, pulverized fuel ash or silica fume. However, testing is necessary to confirm their effectiveness [Hobbs, 1988[5]].

Testing methods to date have concentrated on the susceptibility to AAR. The accelerated tests yield expansion strains which are not a reliable quantitative measure of either the rate of expansion or total expansion which may occur in the

Dams and hydro plants which have been affected by AAR, grouped according to reaction type and date of construction

Date of construction \ Reaction	ASR Aggregates: opal, flint, chalcedony, cristobalite	ASSR Aggregates: graywacke, argillite, gneiss, granite, phyllite, arkose, sandstone	ACR Aggregates: argillaceous dolomitic limestones
1900s	Matabitchuan, Canada Pathfinder, USA		
1910s	Buck, USA	Warm Springs, USA	
1920s	Parker, USA Coolidge, USA American Falls, USA Gibraltar, USA Horse Mesa, USA Morman Flats, USA Hound Chute, Canada Wyman Station, USA Steenbras, RSA Illsee, Switzerland	Huntington, USA Drum Afterbay, USA Maentwrog, UK Trawsfynydd, UK Gydynys, UK Hendormor, UK	
1930s	Stewart Mtn, USA Wildhorse, USA Gene Wash, USA Copper Basin, USA Owytree, USA Beauharnois 1, Canada Bartlett, USA	Chambon, France Santeetleh, USA	
1940s	Green Mtn, USA Matilija, USA Shasta, USA Gerlos, Austria Blogtjern, Norway Churchill, RSA	Fontana, USA Maury, France Friant, USA Peti, Brazil Hiwassee, USA	Chickamauga, USA
1950s	Val de la Mare, UK Beauharnois 2, Canada Saunders, Canada Owen Falls, Uganda Kariba, Zimbabwe/Zambia San Esteban, Spain Poortjieskloof, RSA Keerom, RSA	Castelnau, France Hirakud, India Temple, France St. Mary, Canada La Tuque, Canada	Bimont, France
1960s	Beauharnois 3, Canada Sartigan, Canada Roode Elsburg, RSA Paul Sauar, RSA Hunderfossan, Norway Stampdritt, RSA Pietersfontein, RSA	Dinas, UK Lady Evelyn, Canada Portodemouros, Spain Mactaquac, Canada Rihand, India Waterton, Canada Warsak, Pakistan	
1970s		Salas, Spain Moxoto, Brazil Kamburu, Kenya Rapide des Iles, Canada Tarbela, Pakistan	
1980s	Piedro de Aguila, Argentina		
1990s	Pak Mun, Thailand		

prototype. Test methods to determine the potential magnitude of expansion remaining are urgently required, but are not yet available.

In some structures, it has been found that the expansion ceases after 30 years or so, while in others it has continued unabated for 50 years. This may be related to the supply of alkalis. In some cases the alkalis are supplied primarily by the cement, while in others they may be supplemented from the aggregates themselves. In the first case there may be a limit to the supply, while in the latter case the supply may be effectively unlimited, allowing the reaction to continue indefinitely [Grattan-Bellew and Danay, 1992[4]].

2. Case histories

2.1 Mactaquac

This plant, on the St John river in New Brunswick, Canada, was constructed in the late 1960s with a concrete gravity dam, intake and spillway structures and a 650 MW powerhouse [Thompson and Steele, 1992[6]]. The opening of a longitudinal construction joint in the powerhouse was noticed in the mid 1970s, followed by cracking and spalling of beams in the early 1980s. In 1985, spillway gate 10 adjacent to the intake structure was obstructed as a result of displacement of the end pier into the gate opening. Measurements of clearances around the units in the powerhouse indicated ovalling caused by concrete expansion.

Remedial measures at Mactaquac included cutting thin slots through the intake structure and spillway abutments. This was accomplished using 13 mm-diameter diamond wire saws at five locations along the length of the intake, each with an area of about 550 m^2. Single cuts were made in the spillway abutments. The work was done with the reservoir at full operating level and without interruption to plant operation. Detailed instrumentation and finite element simulations were used to predict and assess the effects of the cuts. In particular, the stress dependency of the expansion strain rates and larger than usual concrete creep were found to be essential considerations when planning remedial measures.

It is anticipated that the slots will need to be recut every four years, to minimize longitudinal deformations of the intake and to maintain gate clearances. The possibility of a wide slot cut using double saw cuts is being considered as an option to reduce the frequency of future cuts.

In the Mactaquac powerhouse, detailed studies using the results of instrument measurements, finite element modelling and a test slot cut have led to the conclusion that local repairs will be sufficient to maintain structural safety for the time being. Grinding of the turbine throat rings has been done at several units using a blade-mounted device. Transverse slot cuts are being considered as a means to relieve ovalling effects in the units. Longitudinal slot cuts or the installation of slip joints in the penstocks are also under consideration. A continuing programme of grouting is being carried out to help control leakage. So far there is no sign of the rate of AAR expansion slowing down, and it is assumed that it will continue for at least the next 25 years.

2.2 R.H. Saunders

This plant, on the St Lawrence river in Ontario, Canada, was commissioned in 1958 and is incorporated in a 950 m-long dam connecting the Ontario shore to the New York State shore with the international border passing through the centre [Tang, Danay and Ho[7]]. The plant contains 16 generating units which are immediately downstream of the gravity dam intake in an integral mass concrete structure.

Evidence of abnormal behaviour of the units was first recorded in 1972 in the split phase protection relay current of the generators. Investigations revealed that the stator had been deformed into an oval shape, and the air gaps had reduced in the longitudinal axis. In 1978, when the turbines were removed for adjustment of the blade angles, it was found that the throat rings were being squeezed, which was also reducing clearances in the longitudinal axis. In addition, jamming of the supporting bracket keys was noticed, along with other operational problems caused by tilting and ovalling affecting the head-cover and guidevanes. Since 1980, the stators have been remounted with radial freedom-type sole plates to accommodate the ovalling distortions. The throat ring closure problem was addressed by grinding the throat ring of all the units at least once, and in several cases twice. In 1990, a comprehensive investigation programme was initiated, which clearly identified AAR as the root cause of the problems, and a long-term remedial programme was developed.

It was found that AAR would not seriously affect the structural stability of the plant, but that continued grinding of the throat ring was not possible, since it would reduce the thicknesses below acceptable criteria in the near future. Consequently, a slot cutting scheme was developed, using a 15 mm-diameter diamond wire to cut an area of about 560 m^2 transversely between the units. The first cut was completed in early 1993 between units 5 and 6. This first cut was thoroughly analysed and instrumented, and a further two cuts are planned for 1994. Additional cuts to relieve the compressive stresses in the throat rings and supports at all 16 units in the powerhouse are planned to be completed by 1998 [Ho, Dobrowolski, Adeghe and Tang, 1994[8]].

2.3 Lady Evelyn

This dam, on the Montreal river in northern Ontario, Canada, was completed in 1927 [Thomas, Mukherjee, McColm and Everitt, 1992[9]]. Expansion and deterioration of the structure were apparent in the 1960s, and the severity of the problem led to a decision to replace the dam in 1973.

2.4 Lower Notch

This dam, also on the Montreal river in northern Ontario, was completed in 1969 [Thomas, Mukherjee, McColm and Everitt, 1992[9]]. Tests on potential aggregate sources included checks for AAR, and all met the required criteria at that time. However, experience with the Lady Evelyn dam indicated that similar aggregates had been subjected to AAR and had caused damage. Also, longer term expansion tests showed that significant expansion was occurring. Consequently, further tests with flyash partially substituting the cement were done, and this was found to reduce the expansion to acceptable levels. A combination of 30 per cent flyash with normal Portland cement was finally adopted for mass concrete construction. This selection was made partly because low alkali cement was not available, and partly to reduce heat generation. Core samples taken in 1985 showed the concrete to be in good condition, with no sign of AAR.

2.5 Moxoto

This powerplant, on the São Francisco river in Brazil, was completed in 1977 and within a short time experienced problems of concrete cracking, ovalling of circular openings and loss of alignment of the turbine generator axis [Cavalcanti and Silveira, 1992[10]]. These problems culminated in 1980 with the runner blades scrubbing the throat ring in the draft tubes of all four units.

After collection of instrumentation data and modelling of the powerhouse, it was recognized that the cause of the problems was AAR-induced expansion. It was decided that to cut slots to open the transverse construction joints between the units would be the most efficient measure to attenuate the ovalling and stayvane stressing problems. Slots were cut between units 2 and 3 in 1988, units 1 and 2 in 1989 and between units 3 and 4 in 1991. The area cut at each joint was 700 m^2. The cutting involved using six parallel twisted (or helicoidal) steel wires, each with an outside diameter of 5 mm and spaced at 17 mm centres, which removed 30 mm of concrete over a 90 mm width straddling the construction joint. This procedure left five 12 mm strips of concrete between each wire cut. Some of this material was removed, while some settled into the lower parts of the slot, limiting the closure in some areas. Despite problems, instrumentation data were collected which indicated that the slot cuts had achieved some partial relief of the ovalling around the units, and had also reduced the vertical expansion rates, thus relieving the stresses in the stayvanes.

2.6 Warsak

This powerplant [Khan, Coulson and Day, 1992[11]] is on the Kabul river in the North West Frontier of Pakistan. The plant includes six vertical axis Francis turbines and generators, four of which were installed in the late 1950s and early 1960s, the other two having been added in 1981 and 1982. The intake, penstocks and powerhouse are on the right bank, with the dam and spillway across the original river bed. Problems had been experienced at the plant with relative displacements in the concrete of the powerhouse structure, and possibly also in the dam and spillway structures. In 1988 it was determined that AAR expansion was the cause of continuous movements, although seismic shocks had also caused isolated displacements at pre-established slip planes and cracks.

A programme of remedial measures was designed to address problems with the structures, to relieve stresses in the turbine inlet butterfly valves and connections to the penstocks and spiral casings, to modify the generator stator anchoring and realign the units, and to realign the draft tube gate guides and restore clearances on the gates. In 1989 a failure occurred at the butterfly valve of unit 1 which required an emergency repair. This work was done in 1990 at units 1 and 2 and subsequently at units 3 and 4, along with structural repairs to floor beams, grouting of joints and anchoring the downstream portions of the unit blocks. Further work is planned at units 5 and 6 in the near future.

2.7 Kariba

This 128 m-high arch dam, built between 1955 and 1959, is on the border of Zambia and Zimbabwe [Goguel, 1992[12]]. AAR expansion has been identified from instrumentation data and laboratory tests. The maximum values of expansion were measured in the unrestrained corrector blocks and vertically in the dam, but in the horizontal direction of greatest stress in the dam, minimal or even negative expansion was found. Precise levelling shows a regularly continuing rise in the elevation of the crest, roughly proportional to the height of the blocks, with a present maximum of 60 mm in the centre, increasing at a rate of 2 mm/year. Surface cracks are present on the upstream spillway pier nosings and some minor problems occur with the stoplog built-in parts which require maintenance work.

2.8 Bureau of Reclamation dams

The US Bureau of Reclamation (USBR) has several dams subject to AAR [La Boon, 1992[13]], mainly in the western states. Since 1950, AAR has not been a serious problem. However, at least 14 concrete dams built before 1950 have experienced varying degrees of deterioration caused by AAR. The most severe cases were Wildhorse dam in Nevada and American Falls dam in Idaho, which were replaced mainly as a result of deterioration and loss of strength. The majority of AAR-affected dams owned by USBR have only experienced slight deterioration, which has not affected the structural integrity or stability. The main concern has been with expansive displacements resulting in misalignment of concrete structures and misoperation of mechanical equipment such as gates. Most of these works fall under the USBR's Safety Evaluation of Existing Dams (SEED) programmes. Measures include excavation and replacement of expanding concrete, restraint by anchors, reduction of 'free moisture', and the installation of expansion slots.

2.9 Friant

This dam, constructed between 1939 and 1942 in California, USA, is a straight concrete gravity dam 97 m high, with an integral gated spillway near the centre [La Boon, 1992[13]]. The most severe AAR effects are adjacent to the spillway and at the outlet works gates. In these places a more durable concrete was required, and so pozzolan was not used as a cement replacement there. The expansion has caused the piers to move into the spillway about 48 mm, causing binding of the drum gates during operation. The gates have been modified in the past, but since the movements are continuing steadily at a rate of 2 mm/year, a longer term solution is required. To achieve this, the two outer gates will be replaced by flexible air-filled rubber dam gates in the near future.

2.10 Stewart Mountain

This was constructed between 1929 and 1930 on the Salt river in Arizona, USA [La Boon , 1992[13]]. It is a 65 m-high arch dam, with two thrust blocks, three gravity sections and spillways on both abutments. AAR has caused the centre of the arch to move 152 mm upstream and 76 mm vertically, with visible cracking of the original concrete and appurtenant structures. As a result of the USBR's Safety of Dams programme of investigations, it was decided in 1990 to construct a new spillway, add an overlay to the parapet wall, right thrust block and gravity sections, and to install anchors in the arch and thrust blocks to deal with debonded lift lines. The expansion movements have progressively ceased over the last 30 years and USBR has concluded that the alkalis required for the AAR have been depleted, allowing for the remedial works to be limited.

2.11 Bartlett

This was constructed between 1936 and 1939 on the Verde river in Arizona, USA [La Boon, 1992[13]]. The dam is an 87 m-high multiple arch and buttress structure, and investigations are under way there to assess the significance of AAR. Studies of this dam show reductions in strength and modulus, although it is not certain whether this is as a result of AAR and thus presents a design problem. Two studies are being undertaken: one is examining the use of lithium hydroxide as a concrete admixture to inhibit AAR and possibly corrosion of reinforcement; the other is the development of a non-destructive testing method to determine the presence of AAR by the application of uranyl acetate solutions to concrete surfaces under ultra-violet light.

2.12 Hiwassee

The Hiwassee project [Tanner, 1992[14]] on the Hiwassee river in Tennessee, USA, is one of several plants with AAR in the Tennessee Valley Authority (TVA) system. Hiwassee dam was completed in 1940, and includes a 95 m-high concrete gravity structure with a central spillway section, an intake section and non-overflow sections at each end. The main spillway consists of seven radial gated bays and four sluices. The hydro plant has two units, one of which is a pump-turbine.

Special precautions were taken during the design and construction of this scheme to prevent cracking, including the provision of an extensive instrumentation system. Stresses and deflections increased over time as a result of AAR, and there are cracks in horizontal construction joints at both ends of the dam. The non-overflow blocks adjacent to the spillway have deflected into the spillway, causing the spillway gates to bind. There is also concern that the expansion may overload the spillway bridge. There is also evidence of AAR in the powerhouse. Because of the extent and nature of AAR-induced cracking, seismic safety was not certain.

As a result of these investigations at Hiwassee, the TVA decided on the following measures:

- to install vertical anchors in the dam;
- to cut a slot at each abutment;
- to cut expansion joints in the bridge deck; and,
- to modify the two end spillway gates to allow for a further 25 years of expansion.

The slot cuts at the abutments were done in early 1993 [Newell, Tanner and Wagner, 1994[15]], using a diamond wire saw method. Two wide slots are planned to be cut in the abutments, and may be 20 cm wide at the top, tapering to the bottom using two cuts with the diamond wire saw.

2.13 Chambon

Electricité de France has developed a programme to deal with AAR at the Chambon dam on the Romanche river in France [de Beauchamp and Goguel, 1992[16]]. The 137 m-high concrete gravity dam was built between 1929 and 1934, and includes a straight section leading to a curved spillway section at the left abutment. The structures have been subjected to considerable movements as a result of AAR. The remedial measures for Chambon include the construction of a new structurally independent spillway, reduction of thrusts on the abutment by slot cutting, grouting of the horizontally cracked zone near the downstream face, and elimination of uplift by installation of an impervious membrane on the upper 40 m of the upstream face. The remedial programme is described in detail in the March issue of *Hydropower & Dams* [de Beauchamp, 1994[17]].

2.14 Maentwrog

This dam, on Trawsfynydd Lake in North Wales, UK, was originally constructed as part of the Maentwrog hydroelectric plant between 1926 and 1928 [Thomas *et al.*, 1992[9]]. Since its impoundment in 1928, the dam has experienced leakage problems, especially at the lift joints. Various repairs have been attempted, including grouting, guniting the upstream face, attachment of a glass fibre reinforced bitumen overlain by 'Colcrete' and elastomeric sealing on the upstream face. Following investigations in the mid 1980s, in which the main cause of problems was found to be AAR, a decision was made in 1987 to replace the dam using non-reactive aggregate and partial replacement of cement by flyash; the new dam was completed in 1991.

3. Review of AAR effects and options for remedial measures

3.1 General effects of AAR

The rates of concrete expansion as a result of AAR have typically been found to be in the range 20 to 200×10^{-6} mm/mm/year. The range is dependent on the strength of the reaction but also, very significantly, on the degree of restraint against expansion applied by the structural configuration. More restraint leads to a lower expansion rate. In effect, unrestrained expansion rates apply vertically in dams, but restrained rates often exist horizontally.

The expansion in a restrained condition tends to cause the development of compressive stresses. These are dependent on the duration of the reaction, its rate and the degree of restraint. The in-situ stresses may also contain a component of annual thermal cycle strains and stresses in addition to long-term AAR growth effects. Direct AAR expansion stresses have seldom been found to exceed 3 or 4 MPa, although in stress concentrations higher values can exist.

AAR in structures usually causes surface cracking, which is often shallow. This may be caused by gradients of alkali concentrations near the surface. These surface cracks may induce further deterioration, but may not be structurally significant, although they can be used as an indicator of principal stress directions in the concrete interior.

Structural cracks may occur at areas of stress concentration or structural discontinuities, for instance at spillway piers, as a result of movements. These can be of significance and frequently require remedial measures.

3.2 Hydro plant structures and equipment

The most serious effects of AAR in hydroelectric plants have been associated with misalignment of the units and loss of clearance of the runners. Local overstressing and occasionally separation of embedded parts have also been of concern.

Distortions of powerhouse superstructures have occurred as a result of overall expansion and has been exacerbated in some cases by the opening of vertical expansion joints.

Local stressing of substructure concrete elements, such as draft tube piers, is often indicated by diagonal cracking at the exposed surfaces. The behaviour of these elements is often complex, because of their highly restrained nature, making assessments of their strength difficult.

Deformation data are usually collected by plant operations staff during maintenance work, and may indicate effects on equipment alignment. Deformation data may identify ovalling of units and misalignments, but often indicate relative deformation, and cannot always be used to diagnose the cause of the movements. Instrumentation in powerhouses is therefore required to obtain absolute measurements. It is very important that integrated measurement systems are implemented with adequate accuracy. Expansion strain rates in powerhouse sub-structures are often highly variable according to the restraints applied. These restrained conditions are important when planning remedial measures, as measures such as slot cutting will relieve stresses and allow expansion rates to increase for a while at least. In such cases, modelling can provide an invaluable tool if it simulates accurately the AAR concrete behaviour. This aspect is discussed further below.

Remedial measures usually begin with modifications to supports, reaming of bolt holes for headcovers and, sometimes, with grinding of throat rings to increase clearances, for example Beauharnois (1985), Mactaquac (1986), Saunders (1992), and Moxoto (1992). In some cases, discharge rings have been replaced or re-anchored, and local repairs have been made to other embedded parts.

However, in cases where the expansion has continued for a long period, more substantial measures are being implemented. These include cutting slots in the structure, for example at Beauharnois (1985), Mactaquac (1989), Warsak (1991), and the provision of alternative supports for beams and slabs. In some recent cases, slot cutting has been done across the powerhouse between the units, for example at Moxoto (1990) and Saunders (1992).

Leakage into the powerhouses as a result of movements of construction joints or sometimes the rupture of embedded piping, is a continuing problem. Local grouting can be effective in some cases, but careful investigations are required to pinpoint the sources and allow grouting to be properly directed.

3.3 Dams

In arch dams there are several cases of substantial upstream and vertical deformations, some as much as 150 mm. These deformations and associated compressions may not be of direct concern in the main body of the dam, except that differential movements may tend to occur, causing loosening of horizontal construction joints. This loss of joint shear strength has been of concern in static and particularly in seismic safety assessments when combined arch-cantilever action is necessary. Local problems may occur at the abutments or spillway openings if significant structural discontinuities exist, since these may cause structural cracking.

In gravity dams, the expansion effects have caused particular concern at changes in geometry: for instance, at the change from a straight section to a smaller curved abutment section, or at spillway piers, where large shear stresses and cracking may occur. Differential expansion caused by varying rates of AAR within the structure may also cause loosening of horizontal joints, possibly leading to concerns about downstream sliding under either static or seismic loading.

Concrete movements have frequently caused problems of loss of spillway gate clearances, with a resulting limitation of gate operation and flood handling capacity. Deformations in these areas may be accompanied by inclined cracking in the concrete supporting the gate guides, which could affect their stability.

AAR effects in more complex geometries may be more severe. Stress concentrations may occur in buttress dams or at intake structures around water passages. In such cases, AAR-induced deformations could directly affect load carrying components.

Mass concrete strength loss has not been a problem in most cases. As discussed above, construction joints have been found to be the most vulnerable areas. Laboratory testing of intact concrete indicates that the tensile and shear strengths tend to decrease first. Compressive strengths frequently remain close to normal levels. The potential reduction in shear and tensile strengths therefore makes structures more sensitive to the effects of stress concentrations caused by expansion forces.

Most remedies applied have been limited to short-term solutions; for instance, improving the shear strength of joints, controlling structural cracking or improving gate clearances.

Grouting and post-tensioned anchors have been used to improve the shear strength of joints and to repair cracks. Slot cutting has been and still is a useful measure to relieve the expansion forces to reduce cracking potential and relieve squeezing effects on gates.

Slots were made at the Santeetlah dam in 1940 by overlapping drill holes. This method has been applied at several other sites since, including Fontana in 1979.

Diamond wire saw cutting techniques have been used recently at some dams: Mactaquac in 1988, 1989 and 1992; La Tuque in 1992; and Hiwassee in 1993. The slots (10 to 15 mm wide) have been cut, and are likely to be recut as required. The development of techniques for cutting wider slots, such as is planned for Hiwassee dam, will be of considerable benefit.

In several cases it has been necessary to install anchors to enhance stability before slot cuts were made. This was the case for the Mactaquac intake, where there was concern that the response to slot cutting might crack the piers between the water passages. In this case the cuts were to be made through the intake with the reservoir at its normal operating level, so a pattern of tendons was installed before the slot cutting began.

Replacement of water stops is also an important and costly item when cutting slots. Approaches have included the use of temporary upstream seals or blister cofferdams, grouted waterstops using various materials, and (most successfully) mechanical waterstops in new large diameter drillholes.

In the long term the problem is less defined. It is not yet possible to predict the limit of expansion. In many cases it has to be assumed that it will continue indefinitely. The approach then becomes one of reinforcement and recutting when required, as part of a continuous monitoring and maintenance programme.

4. Instrumentation and modelling

The analysis of AAR effects in dams has often been accomplished using finite-element methods. Such simulations have been found to be helpful in understanding the existing condition and forecasting potential future effects with or without remedial measures. Areas of potential concrete cracking can be identified and the benefits of various slot cut options can be assessed.

In this approach, the expansion is often input simply as an equivalent thermal load to a linear elastic analysis. This is convenient, but can lead to misleading results if the growth and moduli values are unrealistic. It is essential that any predictive models are first calibrated against reliable historical field data for the structure.

Displacements can usually be simulated with reasonable accuracy if sufficiently accurate instrumentation systems are in place. Invar bar extensometers have been found to be very suitable for strain measurements. The invar is necessary to allow filtering out of thermal effects which are often also present and of the same order of magnitude. Multiple bar systems are used to assess the distribution of strain throughout the structure. Conventional and inverted pendulums also work well. Tell-tales and mechanical joint meters are sometimes helpful but, of course, only give relative movements. Pendulums and extensometers can give absolute measurements which are more useful.

Stress measurements are certainly desirable, but have in many cases been found to be very variable and unreliable. Overcoring stress measurements appear to be subject to spurious expansion and micro-cracking after drilling, possibly as a result of pent up, or latent, expansion potential; if used directly, these can lead to stress results which are too high. Careful inspection of the core can help avoid such problems. In-situ stress cells have been tried, but their stability as far as long-term expansion is concerned is not certain.

The expansion of concrete as a result of AAR depends on many parameters, including environmental conditions, concrete stress levels, the type of reaction, alkali silicate reaction (ASR), alkali silica/silicate reaction (ASSR), alkali carbonate reaction (ACR), age of the structure, and so on. In the finite element modelling, concrete expansion caused by AAR is treated as an initial strain load.

Instrumentation data from Mactaquac, particularly from the powerhouse, have been used to develop and calibrate a stress-dependent concrete growth model for the Mactaquac structures. The powerhouse data were used to develop the model because a historical record of both deformation and stress measurements was available. The influence of stress on ASR-affected concrete is described by Hobbs [1990[18]]: the results of laboratory tests indicate that concrete expansion decreases with increased, applied or induced stress. However, the extrapolation of accelerated expansion test results to the field conditions continues to be difficult, and it appears that the influence of stress on expansion will be more marked in structures than in accelerated tests. Hence, the concrete growth model was calibrated to prototype data.

Literature and field data also indicate that AAR expansion tends to increase the rate of creep in concrete [Blight, McIver, Schutte and Rimmer, 1981[19]]. In the finite element analysis reported in this paper, concrete creep is modelled using an effective modulus approach, $E_{eff} = E_{ci}/(1+\phi)$ where E_{ci} is the instantaneous elastic modulus and ϕ equals 2.5 for long-term loading (concrete growth loads) and 0.2 for short term loading (slot cut response). This modelling of creep is relatively simple and practical, while more elaborate

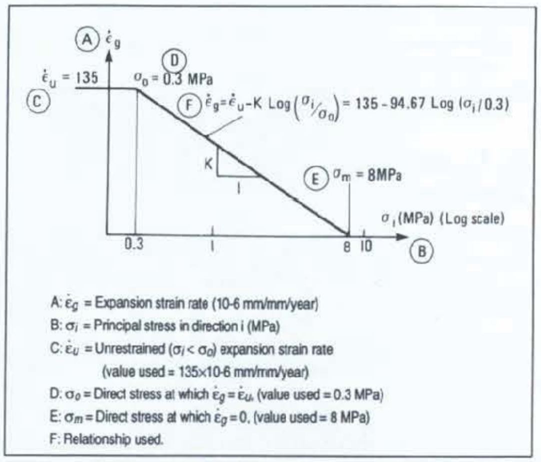

Fig. 1. A stress-dependent expansion rate law.

schemes would require in-situ creep data, which are not available. The model separates creep and stress-dependent concrete growth, although in fact the two effects are interrelated.

The stresses caused by concrete growth increase with time; therefore the concrete growth analysis needs to increase with time in a progressive fashion. The rate of concrete growth at each time step is updated in accordance with the magnitude and direction of principal stresses. As such, concrete growth inputs vary in magnitude and direction throughout the structure. The relationship used between the rate of concrete expansion and concrete stress is given in Figure 1. The variation of concrete expansion with the logarithm of stress provided a reasonable correlation to field observations.

A similar relationship has been developed for the analysis of swelling rock [Wittke, 1990[20]]. The model does not recognize coupling between principal stress directions when stress levels are relatively low, as in the intake. This implies that the expansion rate in each direction is independent. This assumption was supported by observations before and after the slot cutting in the Mactaquac intake. At Mactaquac, observations in the powerhouse suggested that the coupling between stresses in one direction and concrete growth rates in an orthogonal direction occurred at higher stress levels, that is, stresses approaching approximately 6 MPa.

The GROW3D finite-element program [Curtis and Charlwood, 1992[21]] was developed to incorporate the stress dependency and creep in a three-dimensional iterative algorithm. A summary of instrumentation data and the results of finite element modelling for the Mactaquac intake structure before, during, and after several programmes of slot cutting using the GROW3D program is to be presented by Thompson and Charlwood at the 18th ICOLD Congress, in November in Durban [Thompson, Charlwood, Steele, Curtis, 1994[22]].

Finite element analysis can be used in the design of remedial actions to help clarify the following:

- existing structural behaviour mechanisms for correlation with instrumentation data;
- identification and stress analysis of areas of structural concern (including equipment);

- design of slot cutting measures by simulation of the cutting operations and subsequent growth behaviour; and,
- optimum timing of remedial measures and estimates of duration of effectiveness.

5. Conclusions and potential future developments

AAR has been found at a surprisingly large number of hydroelectric plants around the world built in the period between the 1920s and the 1960s. In a few cases AAR expansion has ceased after 30 years or so. In many others it shows no sign of abatement. Reliable methods to predict future expansion do not yet exist; however, there are few cases where significant strength loss has occurred. In most cases, AAR-affected concrete can continue to act as a good structural material. There are examples where the use of pozzolans has inhibited AAR in potentially reactive aggregates.

The effects of AAR on dams and spillways has required repair work, but only very occasionally have they led to abandonment. However, the cost and inconvenience value can sometimes be substantial, involving reservoir drawdown and operational disruptions. Expansion into spillways can directly impinge on gate clearances and operation. Expansion of dams is not always a problem: the problems tend to occur at changes of geometry, for example, from a straight dam to a curved dam, adjacent to spillways or at construction joints.

Temporary repairs frequently include adjustments to gate gains. Longer term solutions to gate problems include flexible gates or slots or separation. The use of wide slots by diamond wire saw cutting may extend the life of such measures. In arch dams, where large movements have occurred and are continuing, vertical anchors have been used to improve lift joints. Grouting has been used frequently to try to control leakage with varying success. High precision instrumentation and monitoring and appropriate finite element modelling can provide useful inputs to dam safety analyses and the design of remedial measures.

The GROW3D finite element model has been developed, which simulates the effects of concrete growth, creep, and the stress-dependent nature of this phenomenon. This model was initially developed to model the Mactaquac powerhouse structure, and has been used successfully on the intake structure. Calibrations with field instrumentation data verified the model. Time step analyses of slot cutting sequences produced results which compared well with actual measured data. The frequency of recutting thin slots can be predicted if appropriate recognition is given to the stress relief effects of slot cutting on expansion strain rates. The model therefore provides a valuable tool for investigating future structural conditions and the effects of slot cutting, both during cutting and as the slot closes with time. ◊

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References

1. Canadian Electrical Association (CEA), Proceedings of International Conference on Concrete Alkali-Aggregate Reactions in Hydroelectric Plants and Dams, CEA in association with CANCOLD, Fredericton, New Brunswick, September-October 1992. Published by CEA, Montreal, Canada; 1992.
2. **Charlwood, R.G., Steele, R.R., Solymar, Z.V., and Curtis, D.D.,** "A Review of AAR in Hydroelectric Plants and Dams"; CEA Conference (as above); 1992.
3. **Berube, M-A., Dupont, N., Pigeon, M., and Stoian, A.,** "Expansion Test Methods for Mass Concrete Exposed to AAR", CEA Conference (as above); 1992.
4. **Grattan-Bellew, P. and Danay, A.,** "Comparison of Laboratory and Field Evaluation of Alkali-Silica Reaction in Large Dams", CEA Conference (as above); 1992.
5. **Hobbs, D.W.,** "Alkali Silica Reaction in Concrete", Thomas Telford, London, UK; 1988.
6. **Thompson, G.A. and Steele, R.R.,** "Alkali Aggregate Reaction at Mactaquac Generating Station: Remedial Measures Progress Report", CEA Conf. (as above); 1992.
7. **Tang, J, Danay, A., and Ho, M.S.,** "AAR at R.H. Saunders GS - Investigations and Planned Remedial Measures", CEA Conference; 1992.
8. **Ho, M.S., Dobrowolski, E.M., Adeghe, L. and Tang, J.H.K.,** "Concrete Growth Mitigation Project at Saunders Generating Station", 56th Annual Meeting of the American Power Conference, Chicago, USA; 1994.
9. **Thomas, M.D.A., Mukherjee, P.K., McColm, E.J., and Everitt, M.F.,** "Case Histories of AAR in Hydraulic Structures in the UK and Canada", CEA Conference (as above); 1992.
10. **Cavalcanti, A.J.C.T and Silveira, J.F.,** "AAR at Moxoto GS - Remedial Measures Development and Implementation", CEA Conference (as above); 1992.
11. **Khan, S.H., Coulson, D.M., and Day, H.,** "Effects of Alkali-Aggregate Reactivity at the Warsak Hydroelectric Generating Station, Islamic Republic of Pakistan", CEA Conference (as above); 1992.
12. **Goguel, B.,** "Concrete Behaviour at Kariba Arch Dam", CEA Conference (as above); 1992.
13. **La Boon, J.,** "Long-Term Performance of Stewart Mountain, Friant and other United States Bureau of Reclamation Dams Affected by Alkali-Aggregate Reaction", CEA Conference (as above); 1992.
14. **Tanner, D.T.,** "The Use of Monitoring and Finite Element Analysis in Evaluating Remedial Measures at TVA's Hiwassee Dam", CEA Conf. (as above); 1992.
15. **Newell, V.A., Tanner, D.T., and Wagner, C.D.,** "Checking Concrete Growth", Civil Engineering, ASCE, New York, USA; January 1994.
16. **de Beauchamp, T. and Goguel, B.,** "Chambon Dam Swelling, Historical Background and Remedial Measures", CEA Conference (as above); 1992.
17. **de Beauchamp, T.,** "Concrete Swelling and Reinforcement Measures at Chambon Dam", International Journal on Hydropower & Dams; March 1994.
18. **Hobbs, D.W.,** "Cracking and Expansion Due to Alkali-Silica Reaction: Its Effect on Concrete". Structural Engineering Review, pp65-79; 1990.
19. **Blight, G.E., McIver, J.R., Schutte, W.K., and Rimmer, R.,** "Effects of Alkali-Aggregate Reaction of Reinforced Concrete Structures made with Witwatersrand Quartzite Aggregate". Conference on Alkali-Aggregate Reaction in Concrete, Cape Town, South Africa; 1981.
20. **Wittke, W.,** "Theory and Application with Case Histories", Rock Mechanics, Springer-Verlag, Berlin, 1990.
21. **Curtis, D.C.,** "GROW3D - Three Dimensional Finite-element Analysis of AAR Concrete", Program Manual, Acres International Ltd, Niagara Falls, Canada; 1992.
22. **Thompson, G.A., Charlwood, R.G., Steele, R.R., and Curtis, D.D.,** "Mactaquac Generating Station Intake and Spillway Remedial Measures". Accepted for publication at the 18th ICOLD Congress (Q68, R24), Durban, South Africa; 1994.