Seismic Retrofit of a Large Power Boiler with Base Isolation

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ABSTRACT: In order to improve the seismic resilience of a large (700 tonne) steam boiler, lead-rubber bearings were inserted beneath it during its annual shutdown for maintenance. Such a retrofit is not uncommon for buildings. However, operational constraints, high temperatures, expansion allowances and connecting ducts, structures and services provided a challenge for the design team. An innovative approach was required to meet the requirements for certification of the boiler as a pressure vessel subject to earthquake loading. A three-stage approach from proof of concept to detailed design was followed, and the bearings were installed during September 2009. This paper describes the analysis and design process, the steps taken to protect the bearings from heat with a combination of simple and space-age materials, and the installation.

1 INTRODUCTION

Carter Holt Harvey Ltd's (CHH) No. 8 Power Boiler at Kinleith (Figure 1) is interesting structurally in that it gets its support for all applied loads from water-filled pipes that are part of the steam generation process. This form of construction is unusual for large industrial boilers. With an operational mass of approximately 700 tonnes, the boiler is approximately 20 metres high, 8 x 12 m in plan, and has been in operation for more than ten years. It is supported on four reinforced concrete pedestals at its corners. To allow for approximately 50 mm thermal expansion horizontally, the boiler was originally constructed with one leg fixed, the two adjacent ones guided horizontally on sliding bearings, and the diagonal leg free to slide horizontally. Holding-down ties were incorporated in 2006 to prevent overturning under seismic loads.

Figure 1: Building containing Nº 8 Power Boiler

When checking the ability to hang a maintenance platform from the boiler, Dobbie Engineers Ltd (DEL) discovered that they were unable to as a preliminary check showed it apparently did not meet the ASME Boiler and Pressure Vessel Design Code. The decision was made to undertake a full design analysis of the boiler structure. DEL was commissioned to undertake this work and discovered that the structure did not meet the Code load combinations that included seismic ones. Their initial analyses suggested that the boiler structure would meet the Code for seismic loadings of about one-third of the current requirements for the site. Work by DEL and CHH on strengthening and remediation options showed that solutions of the normal kind (e.g., gussets, doubling plates, or similar) would be extremely costly and involve extended outage periods because of the complex space-frame design of the boiler and the large, difficult weldments it contained. Cost aside, the expected long outages were unacceptable to the mill where the associated loss of production would run to hundreds of thousands of dollars per day. It was therefore decided to investigate the option of isolating the boiler and reducing seismic loads by means of lead-rubber isolators. This approach had the potential to solve the problem with minimal intervention to the boiler itself, and be undertaken within a normal annual maintenance shut-down period of two weeks. Cost and feasibility were unknown and outside the expertise of CHH to resolve.

In analysing the problem it had, and determining the appropriate action to take, CHH took into account that the seismic design philosophy of the New Zealand Building Code and its verification methods is protection of life and personnel safety as far as reasonably possible during the design (ULS) event, not only a serviceability (SLS) event. Given the focus on prevention of unsafe pressure release in the boiler codes, CHH and its legal advisers made a decision to ensure that a large, unsafe release of the boiler's high pressure steam and water would (as far as practicable) not occur during a design event. That is, CHH decided to meet the requirements of the ASME boiler code for the ULS design event rather than argue that full compliance was not required for seismic loads.

Beca's specialist earthquake engineers were introduced to the problem and requested to advise on the feasibility of such a solution, together with an opinion on likely cost and possible difficulties.

A three-stage approach from proof of concept to detailed design was followed, and the bearings were installed during September 2009. This paper describes the analysis and design process, the steps taken to protect the bearings from heat with a combination of simple and space-age materials, and the installation.

2 THE INVESTIGATION

2.1 Analytical Modelling

The boiler structure is made up of pipes which carry hot water at 45 bar and 250 °C as part of the steam generating system. A three-dimensional frame is formed by four large diameter corner pipe columns, and connecting horizontal pipes at the top and bottom of each wall of the rectangular box. The walls are made up of small diameter vertical pipes spanning between the top and bottom horizontal pipes which are headers for the flow of water in the walls. The vertical wall pipes are welded to each other over their full height via fins between them. The walls are prevented from bulging outwards at a small number of levels by horizontal steel sections (buckstays) that span between the corner columns/pipes. The external walls also have internal intermediate walls spanning the width of the boiler, and these add to the overall stiffness of the boiler. These components combine to create a very stiff structure which under a design earthquake has a differential displacement (top to bottom) of less than 20 mm over 20 metres.

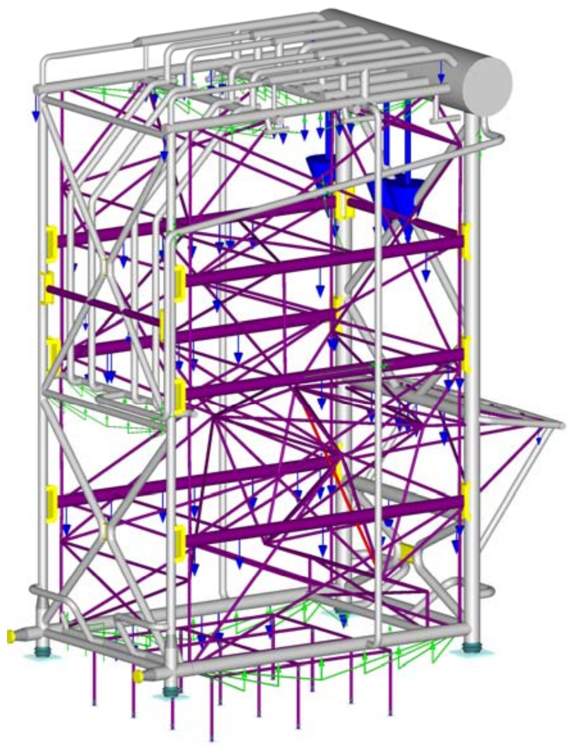

Figure 2: Analytical Model of Boiler

Dobbie Engineers chose to model the structure of the boiler using the AutoPIPE analysis software. This pipework analysis program has a number of advantages over a general structural analysis package. It is customised for the entry of pipe sections and their fluid contents, and it will undertake stress checks to the requirements of the ASME Boiler and Pressure Vessel Code. In particular, it takes into account the different forms of pipe connections when checking joint stresses. AutoPIPE will undertake response spectrum analyses and thermal analysis, but is not well-suited for the modelling of panels such as the boiler walls made up of pipes. Dobbie Engineers chose to model the boiler walls with an equivalent cross-bracing method using tuned braces to reflect the expected deflections of the panel walls. The cross-braces can be seen in Figure 2 as the thin, diagonal lines.

The use of the chosen AutoPIPE modelling method and the assumptions were reviewed and confirmed by a specialist European boiler designer.

Beca was commissioned to work with Dobbie Engineers to confirm the appropriateness of the modelling that had been undertaken in AutoPIPE, and that a deficiency in seismic resilience existed. Beca undertook this by recoding the Dobbie Engineers model into the general structural analysis package SAP2000, and carrying out a number of response spectrum analyses for different representations of the boiler walls. Even though the geometry, material and section properties were available digitally from the AutoPIPE model, the process of converting this into SAP2000 format proved to be a significant task which gave confidence in the use of this process as a check.

Beca's sensitivity analyses confirmed the general level of seismic deficiency that Dobbie Engineers had already identified, and a co-operative exercise was undertaken to improve the modelling of the stiff boiler walls and the influence of the buckstays on the stiffness of the structure.

The outcome of this study was that comparable models of the boiler structure (both using equivalent cross-bracing for the boiler walls) were available in both the SAP2000 and AutoPIPE software packages. It was confirmed that the fundamental natural periods of the existing structure were short enough for there to be a significant chance that base isolation would produce a substantial lowering of seismic design forces.

2.2 Seismic Design Parameters

Concurrently with the analysis modelling checks, the client (Carter Holt Harvey Ltd.) confirmed that the seismic design parameters for the boiler should be in accordance with NZS 1170.5 for a structure of normal Importance and with a 50-year design life. They also confirmed that the site subsoil Class should be taken as C, and that the Zone Factor should be as specified for the Kinleith site in NZS 1170.5. A number of previous studies for the boiler and for the site were available.

2.3 Base Isolation – Proof of Concept

Base isolation works by introducing flexibility beneath the structure so that the fundamental natural modes of the structure are not so susceptible to excitation by the design-level ground shaking. This comes at the expense of needing to allow for the associated displacements of the superstructure relative to its foundation.

The No. 8 Power Boiler at Kinleith is fuelled by both gas and bark – the latter being fed into the boiler down an inclined grate from elevated hoppers. In addition, there are large air intake ducts, exhaust ducts, water supply pipes, and generated steam pipes - the latter two at high pressure and temperature and carrying their own risks. There is also a network of elevated access structures surrounding the boiler. The existing foundation support system meant that the only movement between boiler and connecting ducts, pipes and service access structure that needed to be allowed for was the thermal expansion of the boiler – a maximum of about 50 mm.

It was therefore important that an early estimate of the likely additional allowance for displacement that would be required for a base-isolated boiler be determined. It was recognised early on that the cost of allowing for this additional displacement could well be much greater than the cost of the bearings and their installation.

A field study of the connections with the boiler and the likely clashes between the base-isolated boiler and surrounding structures was undertaken by Beca.

At the same time, Beca's Dr David Whittaker undertook a preliminary design (Figure 3) of a lead-rubber bearing system in accordance with a displacement-based iterative procedure he developed some

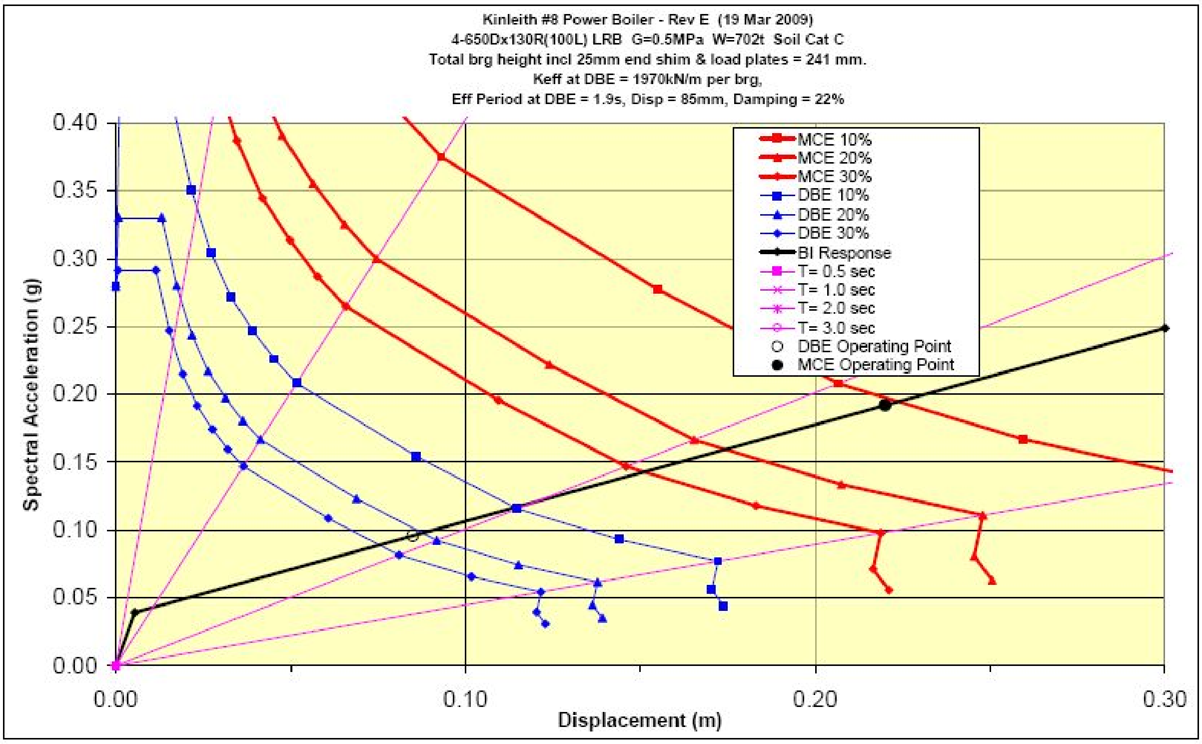

Figure 3: Bearing Performance based on a Single Degree of Freedom Model

years ago. Using a single degree-of-freedom model, the likely axial loads in the bearings, average rubber properties, and the NZS1170.5 seismic design parameters, a bearing height, area and lead core diameter was determined that was within the range of those supplied by international manufacturers. The optimal bearing (one per corner of the boiler, and all four assumed to be identical) was predicted to give a maximum horizontal displacement of approximately 85 mm under the 500-year return period design-level shaking. The lead core was sized to give a nominal yield level base shear of five per cent of the boiler weight, and the bearing was expected to generate 22 % damping in the fundamental base isolation modes. The fundamental (base-isolation) mode of vibration would have a natural period of 2.6 seconds. The base isolation was predicted to lower the otherwise expected design-level seismic base shear by a factor of nearly three.

The predicted decrease in seismic base shear indicated by the base-isolation was in line with early rule-of-thumb estimates, and the design-level horizontal displacements were considerably less than earlier estimates.

An additional benefit of the base isolation was shown to be that the boiler would not now need a holding-down system at each corner to prevent uplift/overturning.

A comprehensive report was prepared which confirmed the feasibility of the base isolation system and the expected costs of procurement, installation, and the alterations to structures surrounding the boiler.

In response to this study, Carter Holt Harvey Ltd decided to proceed with the base isolation. A target maximum horizontal displacement of 100 mm was set.

3 PROCUREMENT OF BEARINGS

In order to be able to procure the custom-made bearings in sufficient time for them to be available for installation during the scheduled annual shut-down, tender documents were issued to a number of international manufacturers on the basis of the bearing design described above. Although it was known that the eccentric positioning of the very heavy steam drum at the top of the boiler meant that the bearing axial loads would not be same at all corners, and might lead to some torsional response around a vertical axis that would cause an enhanced shear on some bearings, it was decided to order all bearings to the same specification. It was judged that the high level of damping that would be achieved in the base isolation modes would counter torsional response.

It was recognised that the response of a base-isolated structure sitting on only four bearings would be more susceptible to variations in horizontal shear stiffness amongst the four bearings than a building structure on 50-200 (such as a hospital). In discussions with tenderers, it was found that none of them would guarantee bearings to a stiffness closer than ± 10 % of the specified value, and within ± 10 % of each other's stiffness. As there was a requirement for all bearings to be tested to beyond design-level, it was decided that the final position of each bearing would be determined by the test results – the two stiffer bearings to be placed at the slightly heavier end of the boiler.

4 CONFIRMATORY ANALYSES

4.1 Analyses of Record

In parallel with the bearing procurement process, it was clearly appropriate to undertake more detailed analyses which would confirm the seismic stress distribution throughout the base-isolated boiler.

Investigations by Dobbie Engineers using their comparable AutoPIPE model indicated that they could satisfy the ASME Boiler and Pressure Vessel requirements for all load cases (including the critical thermal ones) if a seismic base shear of 0.2 g were not exceeded.

Beca therefore proceeded to plan response spectrum analyses of the base-isolated boiler on the equivalent SAP2000 model.

4.2 Inclusion of the Grate

The No. 8 Power Boiler has a moving grate which forms the floor of the boiler. This Kablitz grate "walks" so as to transport the burning bark across the boiler, and the ash falls through a water seal into series of troughs beneath the boiler. The grate structure is supported independently of the rest of the boiler on a grid of 12 short columns (see Figure 2). Detailed consideration was given by Dobbie Engineers and Carter Holt Harvey's maintenance staff as to how the air seal between grate and boiler could be improved – particularly in light of the increased seismic displacement to be allowed for.

It was decided that a series of stops would be introduced between the circumference of the grate and the horizontal ring of headers at the bottom of the boiler so that the grate would be forced to follow the horizontal movement of the boiler. Some slop in the system would allow for differential thermal expansion as the grate and surrounding boiler heat up at different rates.

The analytical models were therefore required to include both the mass of the grate and a contribution from the lateral stiffness of the grate supports.

4.3 Response Spectrum Analyses

Response spectrum analyses were undertaken in SAP2000 using the upgraded three-dimensional model. The design-level loading was applied separately in each orthogonal horizontal direction. The Complete Quadratic Combination (CQC) method was used to combine the three-dimensional mode shapes.

It is interesting to note that there are a number of places in the specification of analysis parameters where the level of damping is to be specified. SAP2000, like its stable mate ETABS, allows the specification of a base-isolation element. For response spectrum analyses, this element is specified as an equivalent stiffness plus a damping ratio. Typical base isolation devices are nonlinear. Natural mode determination and response spectrum analyses are based on linear modelling. The question therefore arises as to how the software takes account of the non-linear behaviour in the fundamental base isolation modes.

Damping is also specified together with the response spectrum, and separately when specifying the method of modal combination.

In order to get realistic results, it is most important that the significance of these different damping specifications be understood. The software manual provides little clarification.

In most base-isolated structures, the first natural mode in each orthogonal horizontal direction has a deformation shape which is effectively an almost-rigid superstructure moving horizontally on a flexible base isolation system. The damping of this mode of vibration is usually more than five times the standard assumption for the un-isolated structure.

The spectral ordinate used to scale the contribution of these base isolation modes therefore can not be taken from the 5 % one applying to the higher modes (as defined in NZS 1170.5), but from one adjusted for the increased damping. There are a number of references in international literature to studies undertaken on appropriate scale factors for converting response spectra.

It was apparent from a comparison of a number of analyses undertaken that the SAP2000 software was able to both distinguish which modes were the fundamental base isolation ones, and to use an internal algorithm to scale those modes for the level of damping specified in the base-isolation element. Further enquiries of the local agent for the software confirmed that the software does have a strategy to examine mode shapes for large displacements across the base isolation elements, and to scale these for damping. We were cautioned that the reliability of this process was not guaranteed.

Alternative analyses were undertaken with the bearing damping set to zero, and the (5 %) response spectrum reduced over the period range of the base isolation modes by a 0.66 factor taken from the Uniform Building Code's section on base isolation (to scale a 5 % damping spectrum to 22 %). The results were very close to each other.

Further sensitivity analyses varying the percentage of damping specified for the use in the CQC method for modal combination confirmed that the results are very sensitive when there are closely-spaced modes. A value of 5 % was used for the final analyses.

5 VERIFICATION ANALYSES

5.1 Modelling of Grate Supports

The procurement of the bearings was on the critical path for their installation during a scheduled shut-down. In the meantime, further consideration was being given to the interaction of the grate and the boiler during the design earthquake. In particular, it was decided to modify the grate support legs at their upper and lower (Figure 4) extents to so that reliable plastic hinges could form under the design horizontal displacements of the boilers. While these hinges will limit the lateral load resistance provided by the grate, they will also contribute to the stiffness and damping of the base isolation system.

Figure 4: Grate Support Plastic Hinge

A series of three-dimensional non-linear time history analyses were therefore undertaken that included the expected characteristics of both the lead bearings and the grate support legs. The rest of the boiler was assumed to remain elastic.

5.2 Selection and Scaling of Earthquake Records

GNS Science was commissioned to select and scale seven earthquake records (each with three components) that were representative of the earthquakes that might occur at the site. It was interesting to note that the duration of the records varied considerably, and that it was necessary to run most of the earthquakes for much of their length to ensure that the maximum response of the base-isolated system was experienced.

5.3 Results of Time-History Analyses

The time-history analyses gave a satisfying confirmation of the previous analyses used for design of the base isolation bearings (single degree of freedom) and for three-dimensional displacements (response spectrum analysis). In particular, it was found that the maximum predicted horizontal displacements at the top and bottom of the boiler were within the allowances used for planning the decoupling of the base-isolated boiler from the surrounding structures. The maximum horizontal displacements at the top of the boiler were about 20 % higher than at the base. The maximum horizontal displacements at the heavier (steam drum) end along the drum axis were twice those at the other end, but within the allowances made in the planning process. A majority of the seven earthquake records gave similar maximum results. The grate support legs were seen to participate significantly in the non-linear behaviour of the base-isolation system.

5.4 Design Verification of Boiler

Using the final bearing performance data, DEL adjusted their AutoPIPE model to reflect the expected dampening properties of the bearings, and the boiler design documentation was completed. This design verification also included external equipment that is supported within the boiler, or spans from the building structure to the boiler. This was submitted to SGS New Zealand Ltd for external design verification. This has been completed and a new design certificate has been issued.

6 INSTALLATION CONSIDERATIONS

6.1 Bearing Height

Considerable effort was put into minimising the effort required to modify the pedestals to accept the lead-rubber bearings by minimising their height so that they would fit into the space between the top of the existing concrete plinths and the base of the boiler. This was achieved so that the boiler remains at the same level as it was before base isolation. Also taken into consideration was the intention to replace the existing sliding bearings one leg at a time. This required the stresses within the boiler from differential jacking of the four legs to be investigated in order to put limits on the lifting displacements.

6.2 Temperature

While early measurements of the likely ambient temperatures in the vicinity of where the lead-rubber bearings would be indicated they were below those acceptable for the rubber, more preparatory work showed that the connecting steel operating temperature at one of the legs was at least 190 °C – well above the bearing manufacturer’s recommended maximum temperature of 40 °C. In what is most likely a world first, an insulating layer the same shape in plan as the top plate of the bearing was introduced above each bearing. The insulation is made up of a 50 mm thick sheet of Cogetherm on top of a purpose-made water-cooled plate through which holes have been drilled and manifolds attached so that water can be circulated. The water-cooled plate (shown in Figure 5) provides a secondary heat barrier which is monitored remotely for temperature and water flow. Cogetherm is a proprietary micaceous material with a low thermal conductivity and

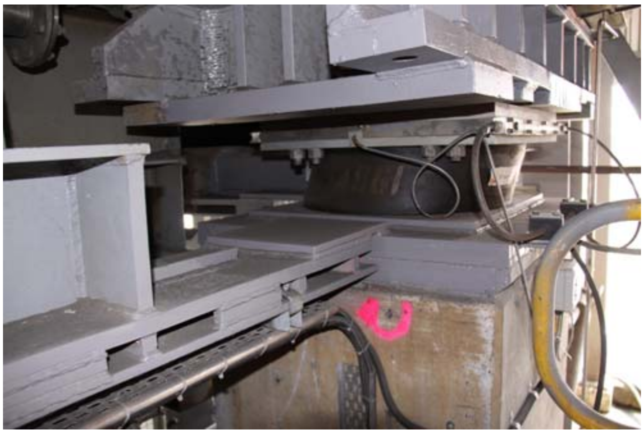

Figure 5: Lead-Rubber Bearing with Water-Cooled Manifold on Top

mechanical properties approaching that of steel.

6.3 Installation

A significant portion of the preparatory work for the base isolation work was able to be undertaken before the scheduled shutdown of the boiler. During the shutdown, the contractor worked around the clock over a period of more than a week to jack each corner of the boiler in turn, remove the existing sliding or fixed supports, and slide in horizontally each bearing. Some anchorages and lifting frames used in previous bearing improvement work on the boiler were able to be adapted for the operation. The thorough planning resulted in there being very few hitches, and the work was finished on time.

6.4 Creep and Thermal Displacement Startup and Shutdown

Prior to base isolation, the feet of the boiler were constrained so that horizontal thermal expansion took place radially outwards from the fixed corner. The direction and quantum of the necessary allowances for service connections, gaps, and seals between the grate and main boiler were predictable. With all four feet placed on lead-rubber bearings, it was realised that it would be less certain in which direction the base of the boiler would move. There was concern that variability in the bearing shear stiffness and properties of the lead cores might lead to much of the thermal expansion being taken at one bearing, and there possibly being a rachetting effect during multiple heat-ups and shutdowns.

Figure 6: Lead-Rubber Bearing with Thermal Displacement Restraints

The thermal expansion/contraction takes place over approximately 12 hours. The thermal displacements are enough to yield the lead cores, but the creep property of lead is such that the stresses induced in the lead are dissipated in a shorter time. It is expected that the relative shear stiffnesses of the rubber part of the bearings will control the final horizontal displacements.

To remove all doubt as to where the boiler would end up in plan, brittle restraints were introduced across the bearings (see grey structure in Figure 6) so that the expansion would take place horizontally in the same constrained way as before base isolation. The securing bolts are sized to shear just above the force level calculated to control the thermal expansion, and the constraints will fall away. The photo to the right shows a typical constraint. This action was not modelled in any of the seismic analyses, but is not expected to alter significantly the base isolation effect or benefits.

7 CONCLUSIONS

In what appears to be a world-first, base isolation has been retrofitted beneath a 700-tonne power boiler during its annual maintenance shutdown period. The seismic resilience of the boiler in its operating condition has been raised by a factor of almost three to meet standard norms for the site and type of equipment.

An innovative solution to limit the conduction of heat to the lead-rubber bearings has been found. Concerns over the direction of thermal expansion of the base being unpredictable have been countered by a brittle constraint system which should not detract from base isolation being achieved in an earthquake.

A series of increasingly more sophisticated structural dynamic analyses have been shown to confirm progressively the designers' early confidence in the viability of a base-isolation retrofit scheme to provide the appropriate level of seismic resilience to the boiler. In particular, no significant retrofit of the water-carrying pipes forming the boiler structure was required, and the work could be completed without costly and unacceptable interruption to the production in the associated pulp and paper mill.

Checks carried out during a two-day outage six months after installation have confirmed that the boiler mounting system has behaved according to the design expectations - with no unexpected displacements of deformation in any of the boiler components.

ACKNOWLEDGEMENT:

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