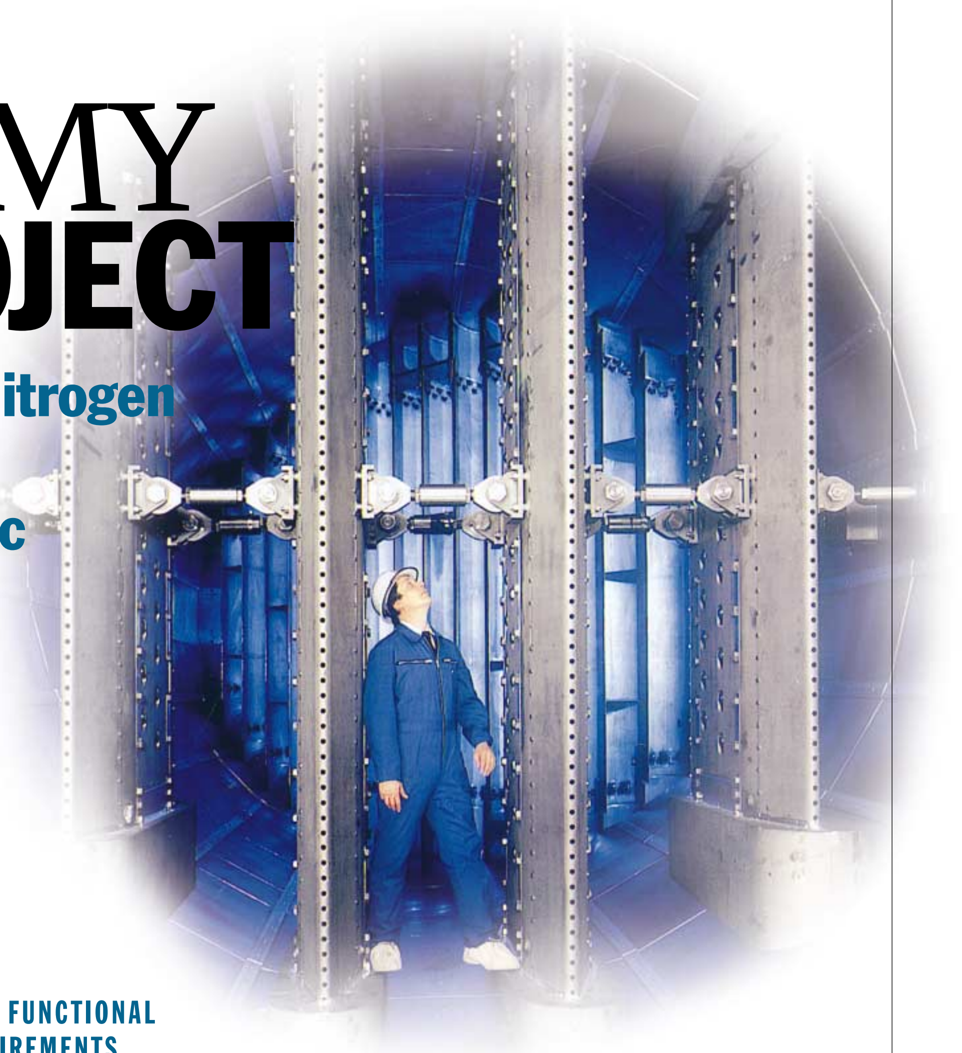
ANATOMY OF A PROJECT



Designing the Liquid-Nitrogen Injection Rakes for the European Transonic Windtunnel Project

EDITOR'S NOTE: This article was written for *Heat Engineering* by Ian Glendinning, who was Lead Technology Engineer for Foster Wheeler Energy Limited during the ETW project. He is currently Principal Consultant Construction Engineer.

In the Fall 1993 issue of this magazine, an article reported on the substantial contributions of Foster Wheeler Energy Limited (FWEL), based at Reading in the United Kingdom, to the prestigious European Transonic Windtunnel (ETW) project. The state-of-the-art windtunnel, a cooperative project financed by the governments of Great Britain, France, Germany and The Netherlands, was designed and constructed by many companies from various countries.

The £240-million aerospace research facility, located near Cologne, Germany, and successfully commissioned last year, boasts an impressive list of statistics, high-tech applications, and innovative features. Figure 1 summarises the key features of the project and Foster Wheeler's scope within it. This article, however, focuses on one particularly novel feature: the design and supply of liquid-nitrogen injectors, or 'rakes,' and the unique challenges faced and overcome by Foster Wheeler's Technology Group.

RAKE FUNCTIONAL REQUIREMENTS

The purpose of the 'rakes' is to inject liquid nitrogen (LN_2) into the tunnel gas stream to provide the cooling necessary to balance the heat input from the 50-MW compressor, which circulates the gas within the tunnel, and to establish the desired cryogenic operating conditions as low as 90 K (-183 °C) at 4.5 bar absolute. As a large insulated container with inputs of mechanical energy and transfers of latent and specific heat, it was easy to visualise the entire project as a high school physics lab calorimetry experiment on a grand scale.

The rakes span a six-metre-diameter section of the tunnel upstream of the compressor. Even distribution of LN_2 across the flow cross section is provided by a uniform arrangement of atomising spray nozzles along each side of each of four rakes. (See Fig 2, pg. 5)

In order to achieve the necessary heat balance and cooling rates, the rakes are capable of injecting a total of 250 kg/sec of LN_2. However, the rakes must also handle a very high turndown ratio to cover the operating range of the tunnel, whilst maintaining the even distribution and control of injection over the whole range. As a consequence, each of the 230 injection nozzles is controlled by its own valve, individually actuated by the tunnel control system. Again, to achieve the necessary responsiveness, the 'dead' volumes between each valve and injection nozzle is minimised by locating the valves and their actuators close to the nozzles inside the rakes in the cryogenic tunnel environment.

GLOSSARY

Mach Number, M The ratio of the gas velocity to the local speed of sound, i.e., M=1 means velocity equals the speed of sound, approximately 740 miles/hour or 330 metres/sec in ambient air.

Reynolds Number, Re Reference dimension x velocity x gas density/ viscosity. A measure of flow quality and aerodynamic behaviour.

K Degrees Kelvin (90 ˚K= -183 ˚C= -297˚F) (273 ˚K= 0 ˚C = 32˚F)

LN_2 Liquid Nitrogen (Atmospheric Boiling Point 77 ˚K or -196 ˚C)

GN_2 Gaseous Nitrogen.

ETW European Transonic Windtunnel GmbH, the consortium which owns and operates the wind tunnel.

FWEL Foster Wheeler Energy Limited, UK.

FW/AP Foster Wheeler/Air Products Joint Venture, UK.

FWDC Foster Wheeler Development Corporation, USA.

WHY A CRYOGENIC WINDTUNNEL?

ETW in a Nutshell

As a cryogenic windtunnel, ETW operates at temperatures down to 90 ˚K and pressures up to 4.5 bars in order that the circulating nitrogen is much denser and has a much lower speed of sound than ambient air. At such conditions, required Mach numbers can be achieved at lower circulation velocities and much larger Reynolds numbers, closer to real aircraft, can be achieved for a given scale model size.

Test conditions and results can therefore simulate the real-life situation more closely and more efficiently than a conventional windtunnel. Most of the equipment and systems in Foster Wheeler's scope were associated with achieving and controlling these conditions.

RAKE STRUCTURAL REQUIREMENTS

Each rake is demountable for maintenance through the nozzles in the tunnel wall from which it is supported. The nozzle closures on which the rakes are mounted therefore form part of the fully certified pressure-vessel shell.

To enable the rake assembly to be handled in one piece, each assembly had to form a single self-supporting structure. In addition, that structure must also be capable of withstanding the extremes of temperature and the transient rates of temperature change in the cyclically cryogenic operating environment. Finally, because the tunnel itself is internally insulated from the cryogenic environment, it was necessary to ensure that the rake mounting arrangements neither permitted conduction to significantly cool the tunnel shell, nor that the arrangement gave rise to unacceptable loadings caused by the differential thermal expansion between the tunnel and the rakes.

In addition, because the environment is also transonic, the velocity of the incident nitrogen stream is as high as Mach 0.3 in the region local to the rakes. Being just downstream of the first corner in the tunnel circuit, this incident gas flow is

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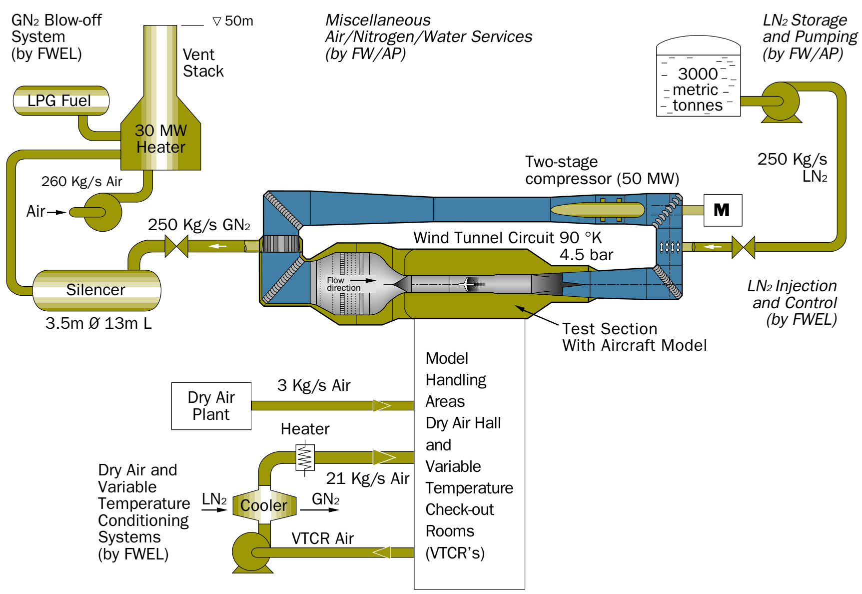
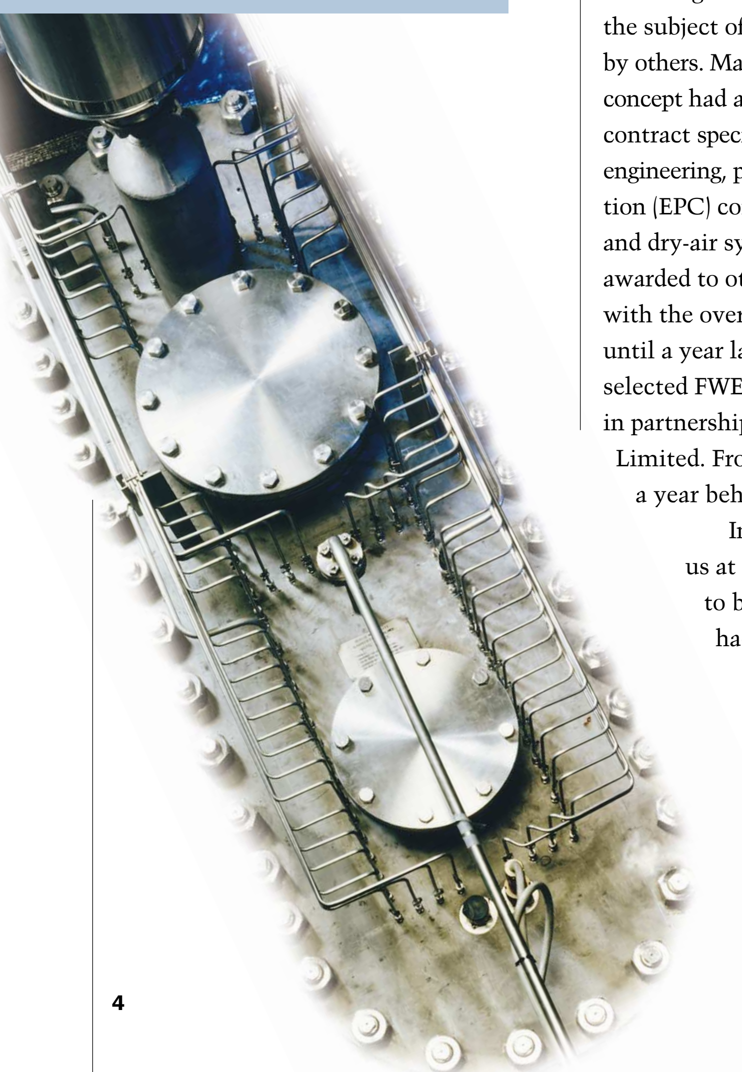
FIGURE 1: MAIN ETW PROJECT COMPONENTS, SHOWING SYSTEMS ENGINEERED BY FOSTER WHEELER



As a process industry contractor, FWEL were clearly experienced in engineering piping and valves; however, it was quite impractical to treat the piping and valves in the conventional manner as separate discrete components.



View of top flange of an injection rake showing the more than 70 injection valve impulse lines and other instrument connections.

not necessarily parallel to the tunnel centreline and is highly turbulent in the wake of the corner turning vanes and any test model upstream. The rake structure must therefore withstand large unsteady aerodynamic loadings. The complementary feature is that the rakes represent a significant drag component affecting the efficiency with which gas is driven around the tunnel circuit. In order to minimise this effect, the rakes required a streamlined aerofoil profile.

THE STARTING POINT

The challenges facing us were not all technical.

The ETW project has a history dating back to 1968. By the time FWEL started work in June 1990, many key items, including the injection rakes, had been the subject of much conceptual design by others. Many features of the rakes' concept had already become frozen in the contract specifications. Furthermore, the engineering, procurement and construction (EPC) contract for the nitrogen and dry-air systems had originally been awarded to others in mid-1989 in line with the overall project plan. It was not until a year later, in June 1990, that ETW selected FWEL to take over the contract in partnership with Air Products (UK) Limited. From the outset, then, we were a year behind the rest of the project.

In placing the contract with us at this late stage, ETW needed to be confident that FWEL had the ability to execute the design, and, having established this, they explicitly sought assurance that we would not subcontract any of the design responsiblity. We had less than two years to design, supply and install these entirely novel items.

In addition to the tight schedule, our major concern was the advanced state of design and manufacture of the windtunnel pressure shell. At the very time we were starting to design our rakes, the tunnel design was not only complete and approved by TÜV Rheinland, the responsible inspection authority, but fabrication of the relevant section of the tunnel was the most advanced and would be fabricated, tested and delivered to the project site before Christmas of that year. It was near impossible to negotiate detail changes at the interface as our design developed.

Not only was the schedule tight, but we had a budget cost based on manufacture of rakes basically conforming to the original conceptual design. This left absolutely no scope for any development and testing of prototypes. Although we were designing and supplying what were in effect fully-operational prototypes, it was necessary to keep it simple and to proceed using known technology wherever possible.

Faced with such constraints, we frequently felt like the innocent bystander who, when asked for directions to some obscure destination, could only reply: "Well, if I wanted to get there, I wouldn't start from here."

DEVELOPMENT OF INJECTION VALVE AND NOZZLE DESIGN

As critical components of the tunnel control system, the injection nozzles and valves had already been subject to conceptual development. Processwise, the performance of these components had to be integrated into our design for the nitrogen-injection control system, a subject beyond the scope of this article. Mechanically, they had to be incorporated into the liquid nitrogen distribution piping within the rakes.

As a process industry contractor, FWEL were clearly experienced in engineering piping and valves; however, it was quite impractical to treat the piping and valves in the conventional manner as separate discrete components. The total of 230 valves were distributed along four distribution headers in each of the four rakes. Each header is an 80mm pipe between 3m and 4m long with between 11 and 18 valves at 200mm centres on each.

The conceptual valve design had the actuation mechanism mounted on one side of the distribution header, with the plug and seat on the diametrically opposite side, as close as practicable to the spray nozzle itself. Effectively, the distribution header formed the valve body and would need to be manufactured to the same fine tolerances as any other functional component of the valve mechanism. In a considerable feat of precision engineering, the valve supplier manufactured the sixteen headers with integral valve bodies from single stainless-steel extrusions with circular bore and square external profile and subsequently turned-down sections between each valve body to the pipe outside diameter.

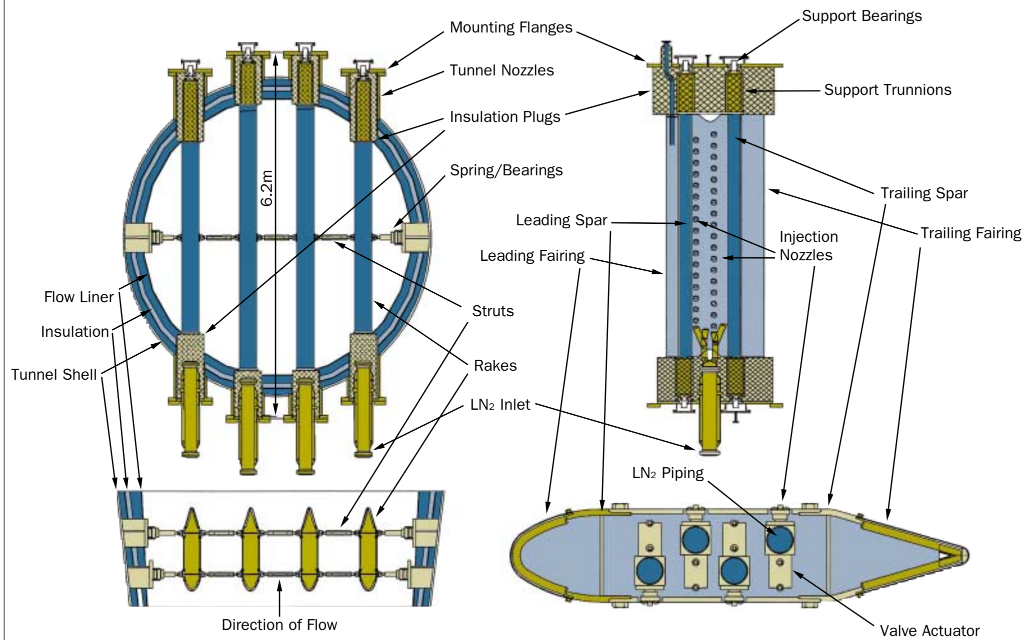
With the valves and actuators in the cryogenic environment, actuation was pneumatic using dry nitrogen. Because it proved impossible to source electrical solenoid actuation, either to operate the valves directly or to control the pneumatic

FIGURE 2: VIEWS AND SECTIONS OF LN_2 INJECTION RAKES FOR ETW

FRONT VIEW OF RAKE ARRANGEMENT

Tunnel section looking downstream

PLAN VIEW OF ONE RAKE



PLAN VIEW OF RAKE ARRANGEMENT

ENLARGED SECTION OF ONE RAKE

actuation within the cryogenic environment, each of the 230 valves had to be supplied with individually controlled pneumatic impulse lines from outside the tunnel.

Furthermore, because operation of each actuator depended on the variable tunnel pressure as well as the LN_2 pressure and the pneumatic supply and exhaust pressures, it was necessary to connect all the actuator exhausts to a common vent header outside the tunnel environment. Together this represented a complex 'spaghetti' of small-bore tubing which had to be accommodated within the rakes and which had to be routed through penetrations in the tunnel closure flanges.

In order to allow the valve supplier to produce and prove prototype valves and to functionally test the final piping, valve, actuator and nozzle assemblies and

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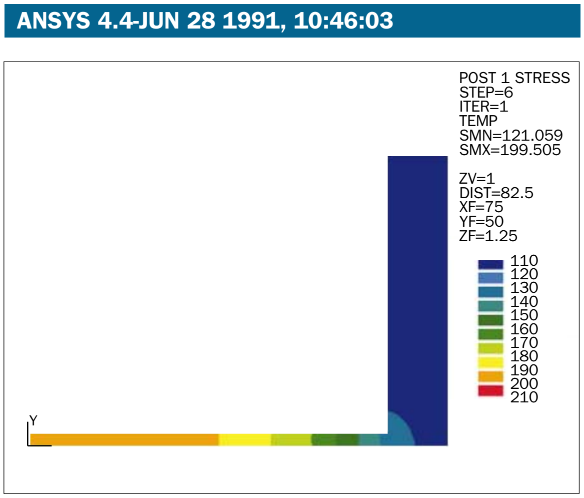
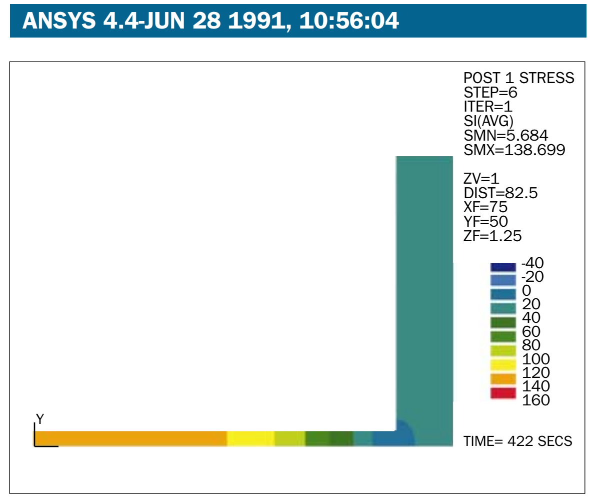
An aerial view of the European Transonic Windtunnel complex in Cologne, Germany.





Transient temperature profiles of quarter-section of 3-D model of rake structure analysed using ANSYS.

As an alternative, the option to use a composite structure had its attractions. It could retain a simple support arrangement and, unlike the option to add in additional supports, it would not interfere with the process of insertion and removal of the rakes through the mounting nozzles.

to then incorporate the results into our process design, it was essential that we place the order for these assemblies long before detailed design of the rakes could be completed. Therefore, in addition to the physical complexity of the interface to be designed between the rake structures and the rake piping assemblies, we had to manage this interface between the two separate suppliers working on separate schedules.

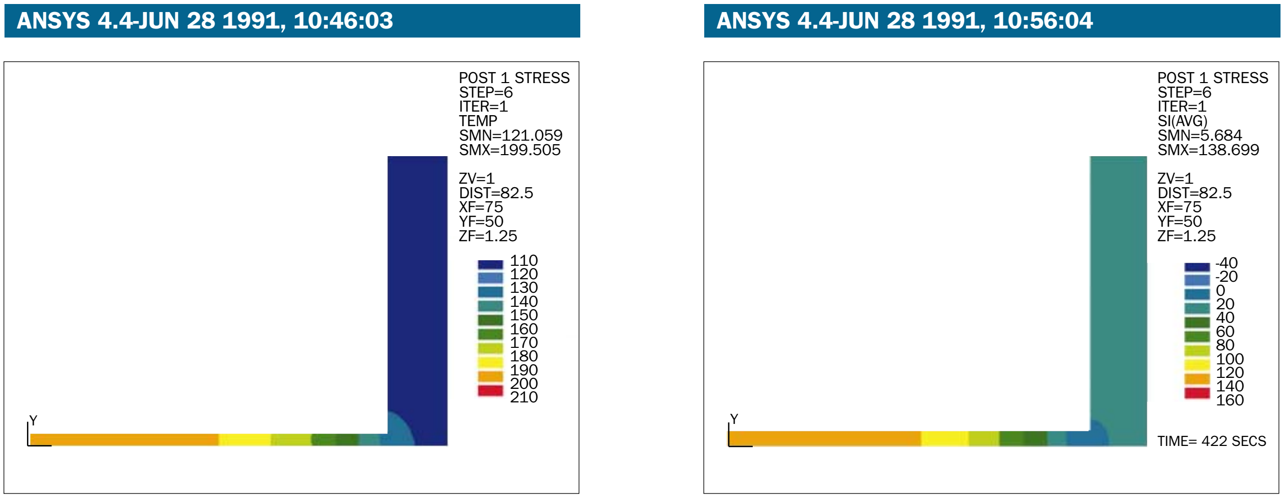
DEVELOPMENT OF THE STRUCTURAL DESIGN

The original rake concept had two spanwise spars with aerodynamic skins and fairings forming the aerofoil section. To minimise thermal-expansion effects, the entire structure was proposed as 'Invar,' a low-coefficient iron-nickel alloy, while the support arrangement consisted of four solid-ceramic ball joints, one at each end of each beam. Three features of the concept were quickly discarded.

First, whilst the use of Invar would reduce thermal expansions of the rake structure, there were still significant differential thermal expansions over the operating temperature range to be accommodated between Invar and non-Invar components and the tunnel shell. More important, with something like five tonnes of Invar structure in each rake, the material cost alone would have consumed the entire budget for the rakes, and the novelty in such a heavy fabrication implied further cost and schedule risks.

Secondly, although theoretically reducing thermal conductivity problems in the design, the use of solid ceramic components in a cryogenic environment also had prohibitive material and component testing implications if they were to be relied upon as the critical support components for the rakes.

Thirdly, the fully-ball-jointed-support concept posed a fundamental dynamic problem: In order to keep our dynamic design analysis within schedule and budget, we had planned to adopt a simple approach whereby the lowest natural frequency of the rakes' structure was higher than any predictable forcing frequencies in the turbulent gas stream. If this were achieved, we could be reasonably certain that the rakes would not be forced into any unacceptable levels of vibration. Any other approach would require detailed response analysis and probably test data to support the inherent uncertainties in such predictions.



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With the simply-supported span fixed by the tunnel diameter, and the 300mm depth specified for the aerofoil section, there was an upper limit on the lowest natural bending frequency achievable. It was already clear that this frequency would be too low in a simply-supported case for a stainless-steel structure or any metallic engineering material with similar stiffness to mass ratio.

We had four possibilities:

1) Use a 'built-in' support at one end;
2) Use non-metallic composite structure with high stiffness to mass ratio;
3) Use additional mid-span supports;
4) Negotiate a relaxation in the range of forcing frequencies specified by the client.

FWEL initially adopted the built-in support option and proceeded to develop the rake design as a conventional stainless-steel fabrication. We knew that a conventional circular trunnion detail could satisfy all mechanical and thermal criteria. Furthermore, we were confident that the massively reinforced tunnel nozzles were more than adequately strong and stiff to support both static and dynamic reactions. Unfortunately, when interface loadings were being confirmed with the tunnel supplier, it became apparent that moment loadings at the large obround nozzles were limited by the sealing-ring performance. Although the ring was a self-energising type, it had an extremely low tolerance to flange rotation, and the supplier was unable by this stage to consider modifications to alleviate our problem.

As an alternative, the option to use a composite structure had its attractions. It could retain a simple support arrangement and, unlike the option to add in additional supports, it would not interfere with the process of insertion and removal of the rakes through the mounting nozzles. However, whilst FWEL are experienced

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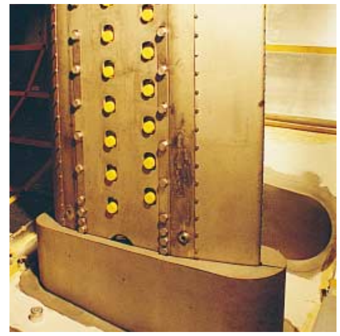
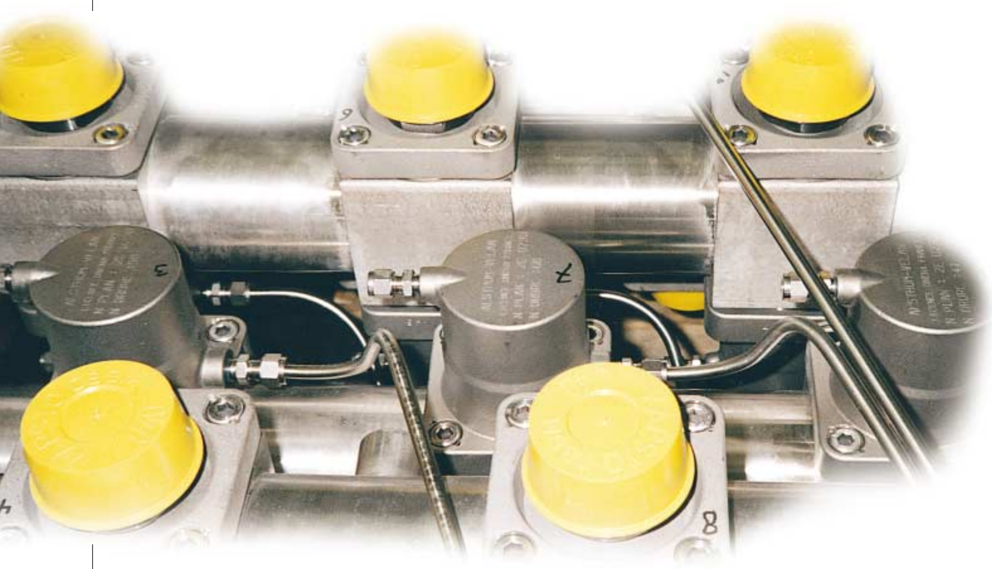


(Above) The first of four LN_2 injection rakes installed in the tunnel. (Below) The injection rakes during final assembly.



Each of the 230 valves was supplied with individually controlled pneumatic impulse lines from outside the tunnel. In this photo, taken during final assembly, the injector nozzles are covered with yellow caps.

Most of the analysis of the various structural and supporting arrangements necessary to optimise the spring design parameters was performed simply using structural elements of the COADE Caesar-II® finite element package commonly used for piping system stress analyses.

in the use of fibre-reinforced composite materials for pressure vessels and piping and similar simple structures, using such material for the rakes would have moved us into areas of design and manufacture more associated with aerospace structures that were entirely novel to FWEL.

In investigating their use, however, we could find no experience of such materials being used for cryogenic structures and so at that time we discounted the possibility. Ironically, some of the most highly-loaded components in the cryogenic tunnel circuit were, in fact, made from carbon-fibre composite—the main compressor rotor blades. However, in view of the budget and schedule pressures, made more critical by this late reconsideration of the basic design concept, we made a wise decision in avoiding this additional area of novelty.

In fact we adopted a combination of options 3 and 4. We were able to obtain client agreement to a reduced range of forcing frequencies as our design basis, but this was insufficient to eliminate the dynamic problem. Providing additional lateral support struts involved its own complications, not least of which for the client was that whilst modifications to the tunnel nozzle/flanges were avoided, this did require retrospective addition of new support points inside the insulated tunnel wall. For FWEL, the design became a compromise between supports which were sufficiently stiff to achieve the necessary fundamental frequency and sufficiently flexible to permit differential thermal expansions without locking in unacceptable thermal loads.

The solution was to use Invar for the major strut components and to incorporate rod-eye type end bearings and Belville-washer type axial springs in an arrangement resembling an automotive shock absorber. Having provided the additional lateral struts, the rake end supports became a combination of spherical and sliding bearings.

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DEVELOPMENT OF THE THERMAL DESIGN

Development of the structural design described above was largely influenced by the need to accommodate steady-state thermal expansions. However, we had two other main thermal criteria to satisfy. Firstly, that heat transfer through rake structural attachments did not lead to cooling of the tunnel shell below specified criteria. Secondly, that thermal transients did not lead to unacceptable loadings within the rake structure.

STEADY-STATE CONDUCTION

Extensions to the main structural members run from the cryogenic environment through the internal insulation in the tunnel nozzles to the bearings and guides inside the mounting flanges. These members carry most of the thermal gradient and were selected as circular trunnions in order to avoid any non-symmetrical gradients and associated secondary stress problems. Design of the trunnions became a matter of selecting their diameter and thickness sufficient to provide the necessary strength and stiffness whilst minimising the total cross-sectional area for heat conduction. It was also necessary to minimise the diameter to ensure sufficient insulated clearance between the trunnions and the tunnel nozzle wall.

At each lower mounting flange, as well as the support trunnions, the main cryogenic LN_2 supply header also enters each rake through the tunnel nozzle. The supply is a 200mm line with a 300mm vacuum jacket. On entering the rake, it undergoes a transition from jacketted to insulated before branching into the four 80mm subheaders within the rake. Also, because of the split supply responsibility between the rakes and the rake piping assemblies, it was necessary to have a mechanical flanged joint between the vacuum jacketted section and the branched transition. Consequently, at the lower mounting nozzles there are not only the cold support trunnions, but also a large mass of cryogenic LN_2 piping, flanges and transition pieces, all of which must be accommodated within the tunnel shell cooling constraint.

Fortunately, both the trunnions and the LN_2 piping are axisymmetric, and the heat flows within them could be modelled two-dimensionally. This simplification was exploited when analysing the designs of these transitions using the ANSYS finite element package, and we were able to successfully optimise their geometry to satisfy the temperature constraint. The same finite element models were also used to show that all thermal stresses within the transitions would be acceptable.

TRANSIENT EFFECTS

In addition to temperature changes during cool-down and warm-up cycles, the temperature of the GN_2 within the tunnel environment changes, under control of the LN_2 injection from the rakes themselves, as model testing conditions are ramped between one set point and the next.

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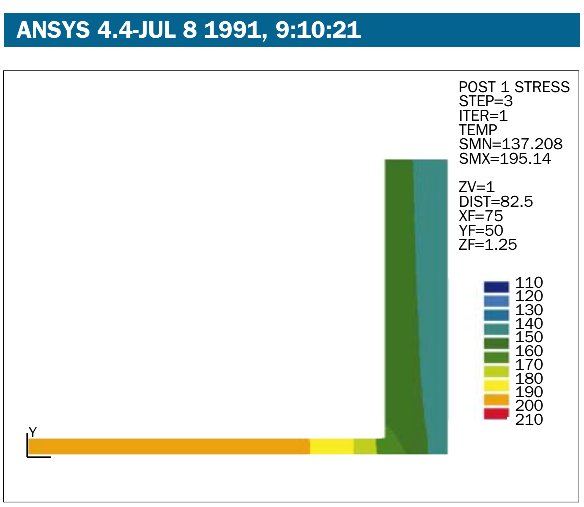
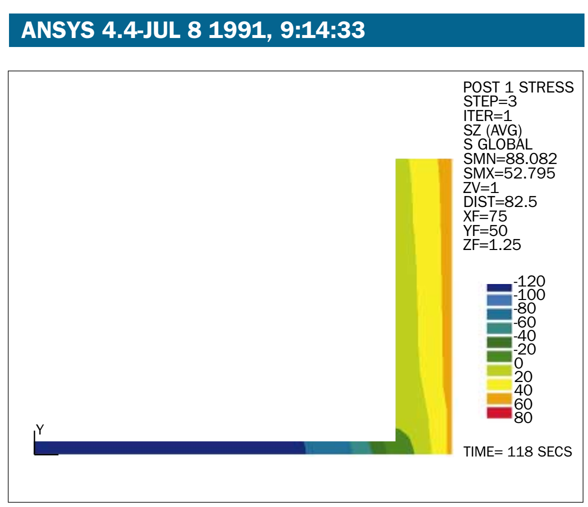
Injection rakes undergo final inspection before commissioning.

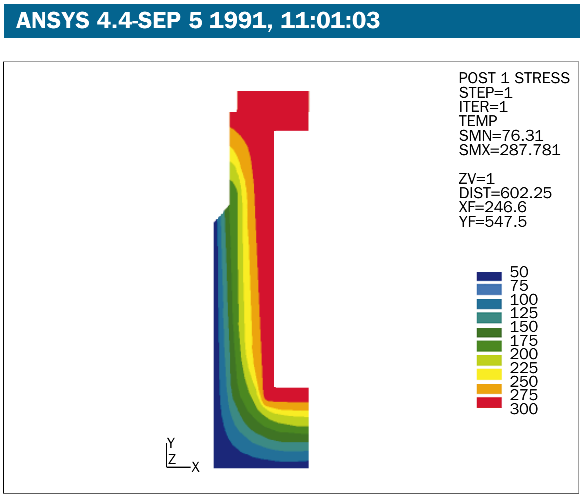
CASE T13

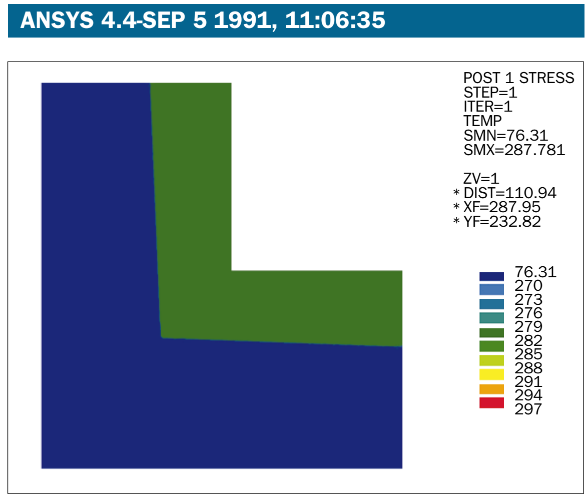




Transient temperature profiles of quarter-section of 3-D model of rake structure analysed using ANSYS.

CASE B02-ETW INSULATION PLUG ANALYSIS-CORRECTED HEAT FLOW





Steady state of analysis of trunnion and LN_2 inlet penetration through tunnel nozzle.

At this point in our design development it was becoming urgent that we translate all our design solutions into detailed drawings suitable for bidding by possible fabricators, if they were to have time to deliver the finished rakes in time for the construction and commissioning schedule.

These operational changes represent in the order of 100,000 transients of typically 40 K or 80 K changes at up to 3 K/s.

At the same time, GN_2 velocities within the tunnel in the rake area are high, around Mach 0.3, highly turbulent and at relatively high gas densities. Heat-transfer coefficients between the tunnel environment and the rake structure are therefore particularly high, and exposed areas of the rakes experience the gas temperature transients very quickly.

Any exposed surface of the rake structure 'sees' any such temperature changes before its internal mass does. The greater the section or thickness of the exposed component, the greater the time lag between its surface and its interior and the greater the transient temperature difference which can exist within it. Where a component is cooled rapidly its surface cools and shrinks, first creating high tensile stresses in the surface of exposed sections.

With high tensile localised surface stresses, the concern is crack propagation from surface defects. For the relevant material thicknesses, heat-transfer coefficients and temperature transients, we were able to predict theoretical elastic stresses well in excess of any allowable secondary stress criterion.

Rather than embark on any complex plastic crack-propagation analysis, we adopted a more pragmatic argument. The filling of equipment with liquid gas can represent a much more severe transient than the one under consideration here. This situation arises frequently in liquid-air and LNG industries and, of course, elsewhere on the ETW project. Furthermore, within the same tunnel transient environment, we were aware of numerous much thicker austenitic stainless-steel structural components in designs already accepted by the project.

Whilst the precedent at least partly alleviated our concerns, we also acknowledged that any potential failures would be progressive and visible on component surfaces. We recommended that our client should inspect and monitor any surface cracks at future shutdowns, much as would be the case for aircraft structures subject to finite fatigue life. Our design would so far as possible incorporate details to minimise the risk of fatigue at critical locations, such as the inclusion of defined radii at welds or changes in structural section.

For transient temperature differences set up between exposed and internal components of the structure, such as the exposed flanges and web of the main structural members, the stresses created are more extensive and need to be controlled within allowable stress criteria. We performed transient thermal and stress analyses of the structure using the ANSYS package to investigate the effects of various heat-transfer coefficients and temperature transients occurring at the various exposed and internal surfaces of the structure. We concluded that it was necessary either to increase the internal heat transfer coefficients or reduce them externally, or some combination of the two.

The possibility of applying thin insulating coatings to reduce the high heat-transfer coefficients at the exposed surfaces was particularly attractive since it would also alleviate remaining concerns over through-thickness effects. A range of paint and adhesive-type coatings was considered and test samples evaluated by cyclic immersion in LN_2. Despite some encouraging results, the extent of testing necessary to ensure reliable performance in extended service in the tunnel environment was impractical within the remaining budget and schedule. Since there were also some drawbacks with the use of coatings—they would hamper future surface inspections, for example—the idea was dropped.

Instead, we chose to introduce additional ventilation paths within the rakes to ensure that heat-transfer coefficients on internal surfaces of the rake structure would be of a similar order to those experienced externally. This resulted in the design of a series of inlet holes along the leading and trailing fairings and openings along the webs of the main structural members to create forced ventilation at the required velocities through the structure and out through the annular openings around the LN_2 spray nozzles.

DESIGN AUDIT

At this point in our design development it was becoming urgent that we translate all our design solutions into detailed drawings suitable for bidding by possible fabricators, if they were to have time to deliver the finished rakes in time for the construction and commissioning schedule.

At the same time, however, we were conscious that, having undergone significant development, our design involved a number of unusual features and had used sophisticated analysis tools. We had to be sure that our assumptions and calculations were correct and fully supported our design before metal was cut. We invited Foster Wheeler Development Corporation (the U.S.-based R&D arm of Foster Wheeler Corporation) to audit the design we had performed to date and the remaining analyses we considered necessary to finally prove the designs. With an established reputation in transient

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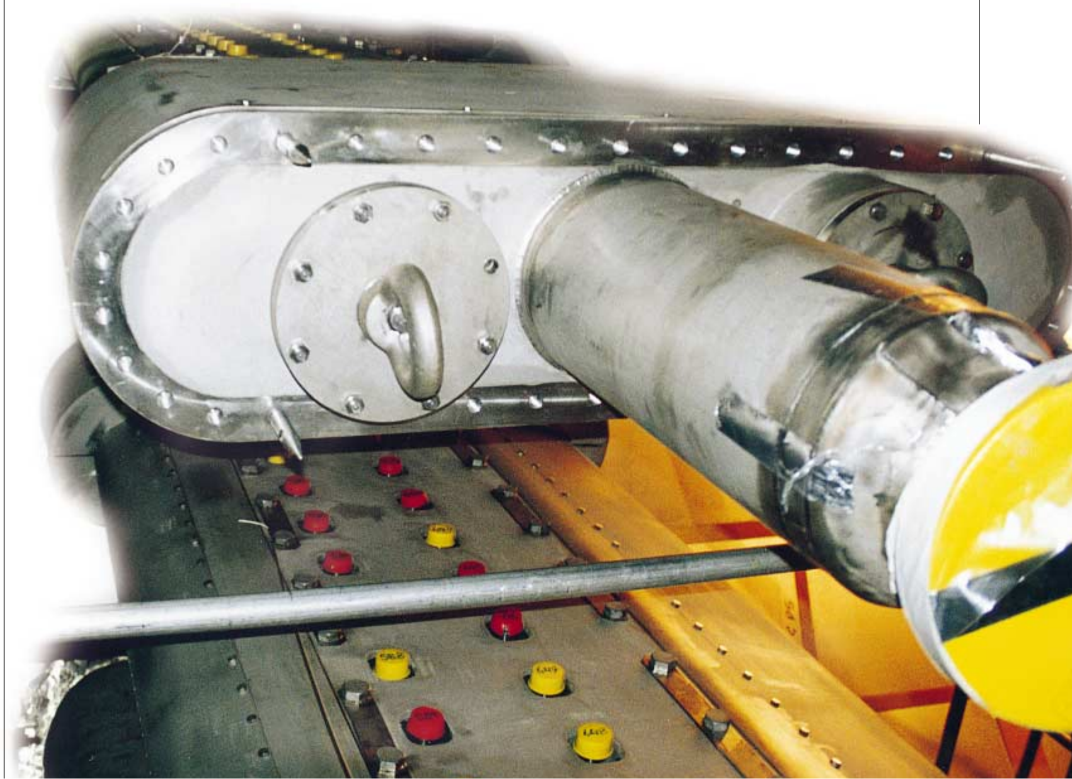
(Above) Since the rakes penetrate the tunnel shell, it was necessary to fully insulate them at the top and the bottom. (Below) A rake being lowered into the tunnel during construction.



(Above) Upstream view of rakes showing ventilation holes in the trailing edges and mid-span struts with springs at the outboard ends. (Below) Sean Jacobs, FWEL Technology Group engineer, inspects two of the rakes during construction.

stress and fatigue analyses using finite element methods (FEM), FWDC were well qualified to comment on our efforts.

The audit found no errors and supported our concerns about the remaining items of uncertainty. FWDC were then also able to assist us by taking on two outstanding design analyses whilst we completed design drawings and analysed the effects of the ventilation cut-outs in the main spar webs. FWDC performed both static and transient ANSYS analyses on the combined thermal and mechanical stresses at the transition between the main structural members and the support trunnions.

Their conclusions demonstrated that our existing design would be satisfactory.

FABRICATION AND INSTALLATION

As already noted, two separate orders were placed for supply of the rakes, one for the piping and valve assemblies, and one for the structure and final assembly. When the order for the structure was placed, our entire design was transferred electronically from our CAD system to the supplier's in what we believe to be a first for FWEL.

This was a unique project for Foster Wheeler. Indeed, engineering the LN_2 injection rakes for the ETW project would have been an unusual technical challenge for anyone. In addition, given the acute budget and schedule constraints, it was a brave commitment for FW to accept the challenge and a significant achievement to meet it.

This supplier was then responsible for production engineering details built into its fully-toleranced manufacturing drawings. They also took on the detailed design and supply of the strut, spring and bearing assemblies, and the special frames required for transport and installation of the rakes.

Having our electronic drawing files right from the start enabled the supplier to produce detailed manufacturing and assembly drawings very quickly. This was also immensely valuable in another way. Where our drawing annotation failed to define or dimension any important details, these were nevertheless fully defined in the graphics files.

Considering the degree of novelty, the supply of the rakes was remarkably successful. Whilst there were routine difficulties in confirming insulation details, some difficulty in achieving satisfactory welding procedures for the Invar components and some correction required for fabrication distortion on the rakes themselves, there was only one problem which led to any schedule slippage.

To ensure that the rakes would fit the tunnel, we had given a great deal of attention to the combined effect of as-built tunnel dimensions, rake tolerances and alignment freedoms. Tolerances and instructions on the production drawings correctly covered the situation, but unfortunately a simple error in the fabrication and assembly sequence prevented a critical overall length tolerance being achieved without some last-minute modifications. With hindsight, the error was not to have developed and applied a sufficiently detailed fabrication and assembly procedure for such a complex and novel item.

CONCLUSION

This was a unique project for Foster Wheeler. Indeed, engineering the LN_2 injection rakes for the ETW project would have been an unusual technical challenge for anyone. In addition, given the acute budget and schedule constraints, it was a brave commitment for FW to accept the challenge and a significant achievement to meet it.

In addition to taking on the responsibility for these unique designs, FW notched up several novel applications in its engineering experience, including:

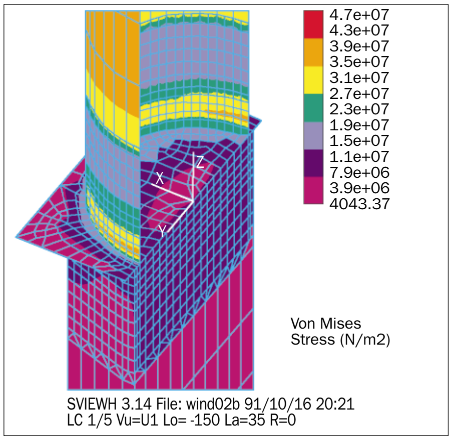
- Use of welded structural components fabricated from Invar;
- Use of transient analysis features of the ANSYS FEM package;
- Electronic exchange of CAD design data with the fabricator;
- Use of friction grip bolting in a cryogenic structure;
- Use of ultra-lightweight aerospace insulation materials.

Following commissioning and tests throughout the operational envelope of tunnel conditions, the European Transonic Windtunnel was deemed ready for commercial operation, which started in 1994. Despite the teething troubles to be expected throughout a project of this novelty and complexity, it appears that the rakes' structures and piping assemblies are performing entirely satisfactorily.

Through the success of this project FW have demonstrated a practical approach to keeping the engineering simple, whilst applying state-of-the-art high-tech methods and materials to the solution of some complex technical and nontechnical problems. ■

STATIC STRESS ANALYSIS

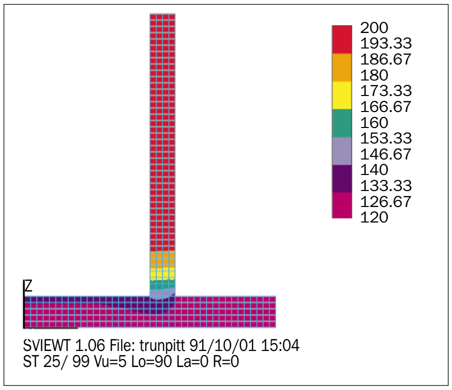
STEADY-STATE THERMAL CASE



Steady-state thermal analysis of the main spar to trunnion transition using ANSYS.

THERMAL TRANSIENT ANALYSIS

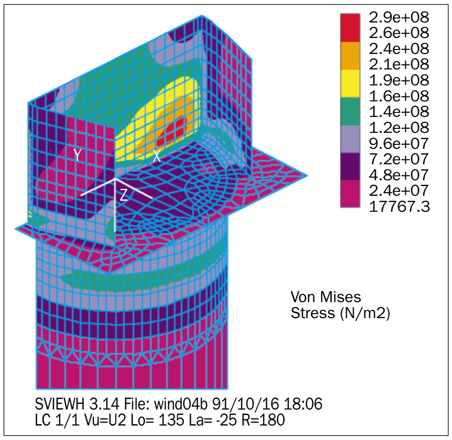
TEMP. AT 250 SEC. DEGREES KELVIN



Transient thermal analysis of the trunnion connection using ANSYS.

STATIC STRESS ANALYSIS

STEADY-STATE THERMAL CASE



Transient thermal analysis of the main spar to trunnion transition using ANSYS.