Geothermal Resources Council *Transactions*, Vol. 21, September/October 1997

Identification of Casing String Failure Modes Using Caliper Data

Brian Wagg, Maurice Slack, Trent Kaiser and Duane DeGeer
Centre for Engineering Research Inc. Edmonton, Alberta, Canada

ABSTRACT

Geothermal well casing failures can occur by several principal failure modes including: buckling; collapse; tensile; and shear. By identifying the specific mode of failure, the loading conditions on the casing can be inferred and appropriate corrective actions taken.

Conventional directional wellbore surveys cannot resolve the local deformations associated with most casing failures. Caliper data, processed using the Caliper Trajectory Algorithm, however, can provide enough information to identify the mode of failure.

Several options for mitigating the effect of formation loads are also presented.

Introduction

Casing failures in steam injection wells used to stimulate Canada's heavy oil reservoirs have received a significant amount of attention in recent years. While steam flows in the opposite direction to that in geothermal wells, many of the casing loads experienced in these wells are also seen in geothermal wells.

This paper presents a discussion of the most prevalent failure modes of thermal well casing due to mechanical deformation of the casing body. A technique to identify casing failure mode, and thus infer a probable loading history, is also presented. Finally, some options for reducing the loads on well casing are briefly discussed.

Casing Failure Modes

A casing failure is defined here as a structural deformation of the casing body that prevents the normal operation of the wellbore. The failure may restrict access to wellbore tools or, in severe cases, limit production rate by restricting flow. Casing connection failures in thermal wells, which include thread jump out, local thread failure and connection body failure are extremely important, but will not be discussed in detail in this paper. Well casing can fail by four principal modes:

- buckling
- collapse
- tensile; and
- shear.

While each failure mode is a result of a different set of loading conditions, response to load combinations is often much more severe than the sum of the individual responses. By identifying the mode of failure, the loading conditions on the well casing at the time of failure can be postulated.

Buckling

Compressive axial loads are caused by thermal expansion of the casing as the well is brought on production, and by frictional loading on the outside of the casing due to formation movement caused by subsidence (Chia, et al. 1989).

Casing buckling occurs when compressive axial loads are applied to sections of casing lacking lateral support, most often due to poor cement jobs, washed out intervals and shale shrinkage due to desiccation. Short, unsupported sections can result in Euler buckling (illustrated in Figure 1), while longer sections may result in helical buckling. It is estimated that for a 550 MPa, 178 mm casing in a 254 mm borehole, an unsupported length of approximately 5 m is required to allow elastic Euler buckling.

Another type of compressive failure is local wall buckling which results in permanent plastic deformation of the casing. One important note is that in the case of compressive axial cas-

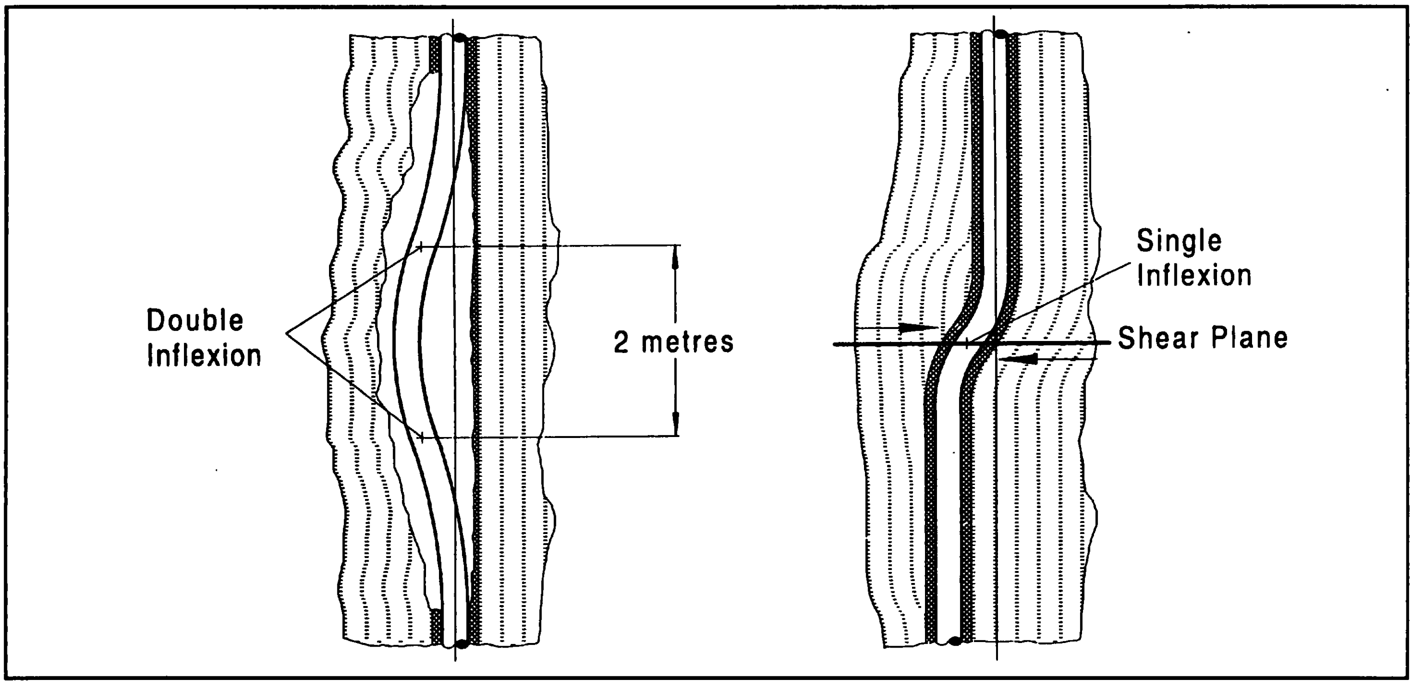

Figure 1. Schematic representation of Euler buckling and shear showing curvature inflexion points.

ing loads due to heating, the process is strain limited, meaning the axial load generated in the casing by a given strain is governed by the stress-strain behavior of the casing material. If the yield strength is higher, then the load transferred across the buckling section must also be higher, since the imposed strains are always higher than that strain. Thus, the buckling load is reached at a lower axial strain.

Collapse

Casing collapse, is caused by high external pressure relative to the internal casing pressure. In geothermal operations, high external casing pressure can be generated by rapidly heating water that is trapped outside the casing. Water may be trapped in the annulus between concentric casing strings or in the thin annulus formed when the cement sheath debonds from the casing.

This type of failure may be avoided by bringing a well on production slowly, thus allowing the wellbore to heat slowly. This may allow time for the pressure generated by the expanding fluid outside of the casing to be dissipated through the low permeability cement sheath and/or surrounding formation.

The collapse resistance of a well casing to external pressure is also affected by axial load (DeGeer, 1991), although the relationship between the two is highly load-path-dependant. Collapse resistance generally increases with compressive axial loads and decreases with tensile loads. Furthermore, although yield strength generally declines with elevated temperature, post yield strain hardening characteristics improve, the net effect being improved collapse resistance. Therefore, the collapse resistance of the casing is greatest when the highest external pressures are generated as the wellbore is heated.

Tensile Loads

Tensile axial loads can be generated during cooling periods after a well is taken off production. Plastic deformation during high temperature operation shifts the neutral load temperature higher, and cooling below this temperature leads to tensile loads. If the compressive plastic strain at high temperature exceeds the elastic range of the material (twice the yield strain) the casing will yield in tension and compression, forming a plastic load cycle.

Additionally, if the cement bond to the casing breaks down during production, thermal expansion of the casing can cause the wellhead to lift out of the ground. Upon cooling, if the base of the casing remains fixed in the reservoir, the wellhead will be drawn back down as the casing shrinks. Friction along the casing will resist the shrinkage and can impart a tensile load on the upper sections of the casing. Cyclic stick-slip behavior can produce incremental lifting of the wellhead with each cycle, much like frost-jacking in reverse. In the application, the incremental movement is manifested as a tensile strain increment in the casing.

The potential for high axial load requires some consideration during connection selection in high temperature applications. The connection must be able to tolerate full pipe body yield under formation controlled loading in both tension and compression. Tension failures are usually characterized by pipe body fractures inside the connection within five threads of the coupling face, or by a thread jump failure in either tension or compression.

Tensile casing loads can also be generated as a result of reservoir compaction. Reduced reservoir pressure during production increases the effective stress in the reservoir rock causing it

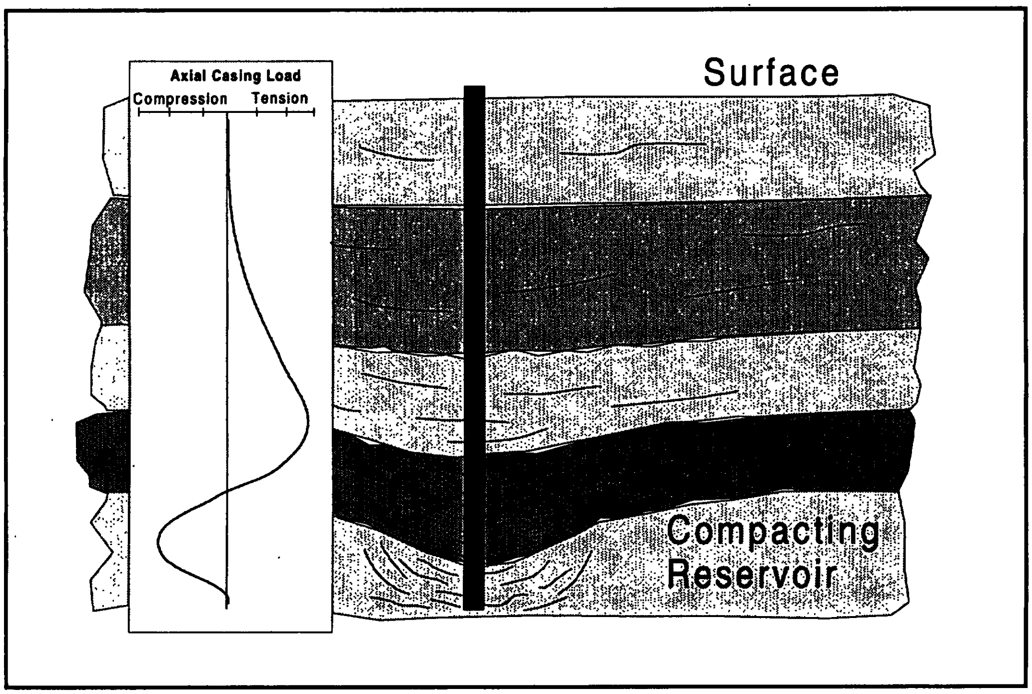

Figure 2. Schematic representation of subsidence causing comprehensive and tensile axial casing loads.

to compact. The overlying strata also deflects downward acting as plates to support the overburdened. Friction between the casing and the down warping strata causes compressive axial loads in compacting zones and tensile loads in adjacent zones (Figure 2). The deflection of the strata, however, decreases as the weight of overburden decreases nearer to the surface. In most cases, surface subsidence is significantly smaller than the change in reservoir thickness (Boade, et al. 1989). As a result, if the casing remains fixed in the uppermost strata as the lower strata move downwards, the casing can be subjected to tensile loads. This tension may persist in the casing as a well brought on production following a workover, decreasing its collapse resistance to pressures generated outside the casing due to rapid heating. If subsidence is severe, the tensile strain can exceed the thermal strain, producing tensile zones during production that could potentially lead to collapse.

Shear

Conventional geothermal wells are typically drilled in tectonically active areas where both the reservoir and overburden are extensively fractured and may contain dormant, or even active faults. Movement along fractures of faults that intersect a wellbore result in a transverse displacement, or shear of the well casing as illustrated in Figure 1.

Studies of movement along faults, fractures and bedding planes (Fookes 1966 and Skempton 1966), suggest that movement is often concentrated in discrete zones less than one metre thick. These concentrated movements can cause extremely high doglegs and severe ovalization of the casing cross-section.

Shear planes are activated by changing the *in situ* stress state. This may consist of increasing the driving force along the plane by increasing the horizontal stress, or by decreasing the resisting force by reducing the vertical stress. Three principal mechanisms exist in geothermal operations for changing these stresses:

- Reservoir compaction and the associated surface subsidence results in reduced vertical stress in the overburden;
- Thermal expansion of the overburden as the wellbore temperature rises during production can increase horizontal formation stress; and
- Tectonic movements generally increase horizontal stress. Divergent plate margins or graben structures may, however, experience reduced horizontal stresses which can also cause movement along planes of weakness in the formation.

Failure Mode Identification

The mode of casing failure may be identified using conventional multi-arm caliper data and a new proprietary Caliper Trajectory Algorithm (CTA) developed by the Centre for Engineering Research Inc.

Multi-arm caliper logging tools are designed, and usually run, to evaluate the radial geometry deformations of wellbore tubulars such as corrosion wall loss, breaks, holes, splits and ovalization. The caliper data is therefore interpreted to quantify these irregularities using the two dimensions of radius and depth. In wellbores where structural deformations are occurring due to geomechanically or thermally induced movement, it is often valuable to quantify the transverse deformation of the hole axis, and thus obtain a three dimensional description of the deformation. The global axis deformation may be obtained

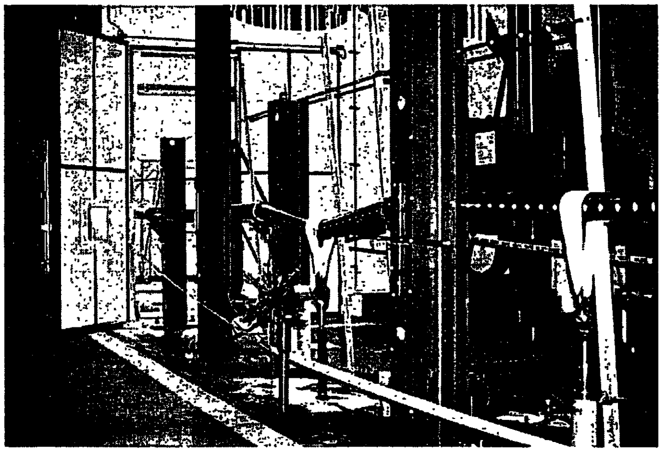

Figure 3. Lab setup used to confirm CTA procedure for interpreting casing deformations.

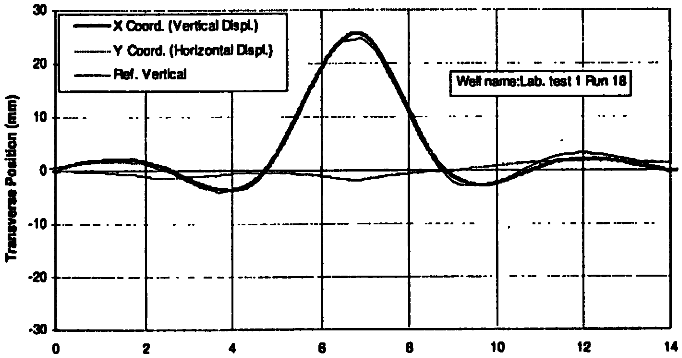

Figure 4. Comparison of caliper trajectory and reference casing deformation.

from directional surveys; but these methods are not able to quantify the highly localized deformations significant to the structural loading imposed on the tubular system.

The CTA computational technique was verified in a full scale laboratory test on a 18.3 m long casing string with up to ten discrete casing deformations representing a variety of failure modes and magnitudes of displacement (Figure 3). Conventional multi-arm caliper log data, processed using the new CTA, was compared to external measurements of casing ovality and trajectory (Figure 4). These tests confirmed that the caliper data can be used to accurately describe the geometry of localized casing deformations.

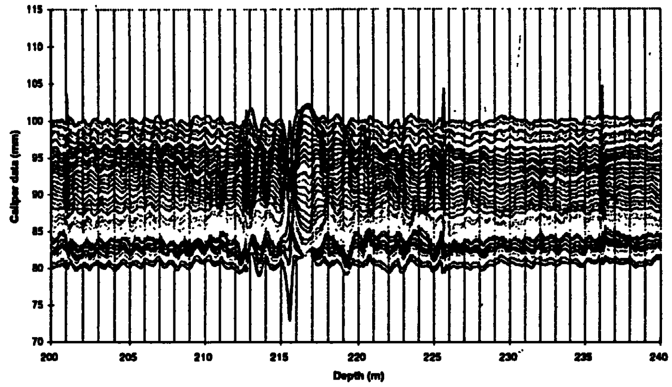

Figure 5. Field caliper data from a steam injection well.

The CTA computation was then applied to caliper data from a steam injection well (Figure 5), which showed significant caliper 'anomalies' over a 40 m interval. A plot of the processed data (Figure 6) shows local casing curvatures up to approximately 400 deg/30 m.

The processed caliper data, over the most pronounced deformation intervals, was visualized by magnifying the lateral and radial deformations, as shown in (Figure 7), to enhance the 'pinching while shearing' deformation shape characteristics of formation shear loading. A similar exaggerated plot of the entire 40 m interval (Figure 8), shows some buckling mode geometries with a definite helical pattern over some intervals.

Although no unique load history can be directly derived from geometry, the deformed shape can be used to suggest possible wellbore loading mechanisms.

Analysis of the most severe deformation from Figure 7 shows that two curvature peaks occur spaced 0.7 m apart, with magnitudes in the order of 300 to 400 deg/30m. Since only two curvature peaks are present, Euler buckling where three peaks are required, can be eliminated as a failure mode. In addition, the measured ovality results are inconsistent with buckling where ovality and curvature correlate. Instead, a single ovality peak occurs between the curvature peaks indicating a shear loading mechanism.

Failure Mitigation

Identifying the most probable casing failure mode can allow the well operator to infer the loading conditions that caused the failure. With this knowledge, modifications may be made to either the well design (Schwall, et al. 1996), or operating procedures to avoid creating the same loading conditions in the failed well or other wells in the field.

Some examples of how understanding the casing failure mode can be used to extend well life include:

- New wells can be oriented with respect to known fracture patterns and *in situ* stress regimes to minimize the effect of shear movements in the reservoir and overburden rock;

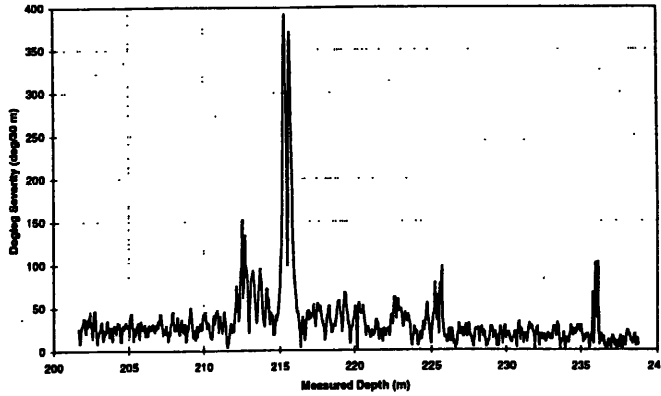

Figure 6. Wellore curvature and flexural strain calculated using CTA technique.

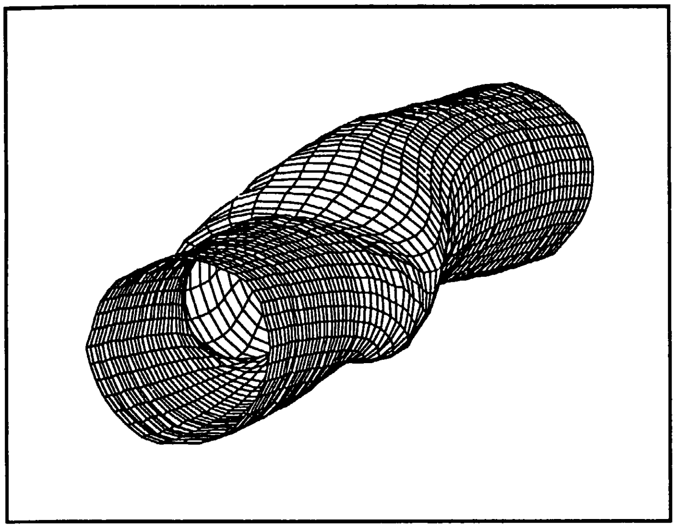

Figure 7. Visualization of local casing deformation with magnified radial and lateral displacements.

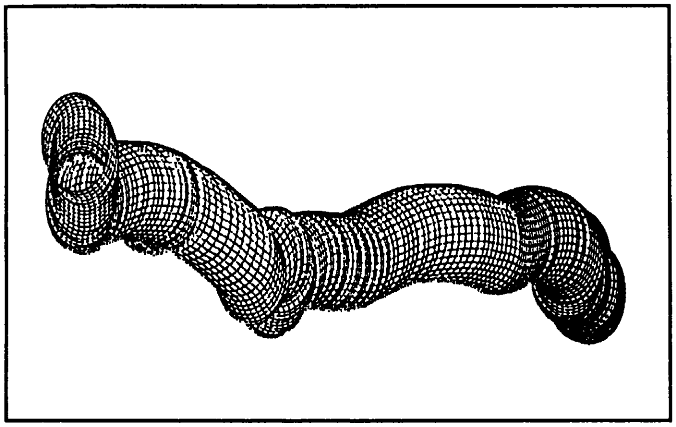

Figure 8. Visualization of 40 m length of deformed casing with magnified radial and lateral displacements.

- Wells can be operated in a manner which minimizes rapid changes in wellbore temperature, either heating or cooling, to minimize compressive and tensile axial casing loads and to allow sufficient drainage time for excess external casing pressure generated by thermal expansion of fluids trapped outside of the casing;
- Intervals where shear is expected may be under-reamed to increase the annulus between casing and intact formation, thereby increasing the allowable shear displacement in the formation before impacting and deforming the casing;
- Recently developed strain absorbing casing elements (e.g. slip joints), which eliminate elastomer sealing elements and provide long strokes, can reduce axial loads generated by subsidence or thermal expansion; and
- Select casing materials and geometries which provide the best resistance to the expected loading scenarios (e.g. bigger and stronger are not necessarily best).

Conclusions

Geothermal well casings are subjected to a combination of loads due to thermal, tectonic and subsidence processes. These loads, usually working in combination, are capable of deforming the casing to an extent where the well becomes unserviceable. The casing body can fail by buckling, collapse, tension or shear.

By determining the mode of well casing failure, using techniques such as CTA processing of caliper log information, new geothermal wells may be designed to both reduce the impact of formation movement on well integrity and to effectively incorporate strain absorbing technologies such as slip joints.

References

DeGeer, D.D., (1991). "Collapse Strength of Cylinders Subject to Axial Tension and External Pressure," Master of Science Thesis, Department of Civil Engineering, University of Alberta.

Chia, Y.P. and Bradley, D.A. (1989). Evaluation of Reservoir Compaction and its Effects on Casing Behavior, *SPE Production Engineering*, May, p. 167-172.

Boade, R.R., Chin, L.Y. and Slemers, W. T., (1989). "Forecasting of Ekofisk Reservoir Compaction and Subsidence by Numerical Simulation," SPE *Journal of Petroleum Technology*, v. 41, p. 723-728.

Fookes, P.G. and Wilson, D.D., (1966). "The Geometry of Discontinuities and Slope Failures in Siwalik Clay," *Geotechnique*, v. 16, p. 305-320.

Skempton, A.W., (1966). "Some Observations on Tectonic Shear Zones," *Proceedings of the First Congress of the of the International Society of Rock Mechanics*, v. 1, p. 329-335.

Schwall, G.H., Slack, M.M. and Kaiser, T.M.V., (1996). "Reservoir Compaction Well Design for the Ekofisk Field," SPE Annual Technical Conference, Denver, Colorado, October, SPE 36621.