Trans-Alaska Pipeline System (TAPS) Seismic Design Criteria and Performance in the 2002 Denali Fault Earthquake

CE A611 Project

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Summary

The Trans Alaska Pipeline was designed in accordance with a set of seismic criteria that addressed the unique geotechnical conditions of Alaska in a comprehensive manner. In addition, the TAPS operator (Alyeska Pipeline Service Company) formulated contingency procedures in the event that a "design contingency earthquake" or "design operating earthquake" occurred. Neither the design criteria nor the contingency procedures had ever been fully tested until the Denali Fault earthquake of November 2002. The report will discuss the performance of the system and the contingency procedures in the context of this event. It will conclude with a discussion of the "lessons learned" and other seismic program changes that have been implemented since then, and those that remain to be completed at this writing.

Introduction and Historical Background

The Trans Alaska Pipeline System (TAPS), built between 1974 and 1977, was a project born in controversy. That controversy caused significant delay in construction and caused a great deal of rework in engineering and design, as the project went through a series of legal challenges. However, the environmental controversies surrounding TAPS were never fully resolved, and aspects of TAPS operation and maintenance remain contentious to this day.

Not least among the issues was the prospect of oil spills caused by strong motion earthquakes. The damage potential associated with earthquakes in Alaska had been vividly demonstrated several years earlier (March 27, 1964) during the M9.2 Good Friday earthquake, which caused major damage and fatalities to the City of Valdez. The fact that

Valdez, as an ice free port, was designated to serve as the oil terminal highlighted seismic risk as a potential vulnerability.

The Stipulations of the Agreement and Grant of Right of Way, issued by the Bureau of Land Management for the pipeline to cross federal lands, stated the following:

> [The Trans-Alaska] pipeline shall be seismically designed, where technically feasible, by appropriate application of the best practicable technology available, to prevent any [crude oil] leakage from the effects (including seismic shaking, ground deformation and earthquake-induced mass movements) of earthquakes.

No specification or further stipulation was made in the Stipulations about how this was to be done; rather, the requirement was to assure that it was done.

Although the original text of the Stipulations was prepared and issued under the auspices of the U.S. Department of the Interior Bureau of Land Management (BLM), it was also adopted by the State of Alaska Department of Natural Resources (ADNR) as part of its grant of right of way to cross state lands.

The Stipulations were the outcome of a number of large studies, most notably the Environmental Impact Statement (EIS). Relevant to seismic issues, the March 1972 *Final Environmental Impact Statement on the Proposed Trans-Alaska Pipeline* contained the following statement:

> …the probability that one or more large-magnitude earthquakes would occur in the vicinity of this portion of the proposed route [the southern two-thirds of the pipeline] during the lifetime of the pipeline is extremely high, in fact, almost a certainty."[1]

The prospect of a large magnitude earthquake along the pipeline, and its possible consequences in terms of spilled oil, assured that seismic design considerations would be of

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[1] Quoted in Peter Coates, *The Trans-Alaska Pipeline Controversy: Technology, Conservation and the Frontier* (University of Alaska Press, 1993).

paramount importance in the design of the pipeline and its major facilities (the twelve pump stations and marine terminal).

This involved the following elements:

- ☐ Identification and zonation of seismological hazard areas;
- ☐ Identification of "design earthquakes" for each zone based on established recurrence intervals;
- ☐ Identification of spectral accelerations appropriate to these seismic zones;
- ☐ Development of appropriate calculation tools to assess earthquake induced stresses, accelerations, displacements, etc. for long pipelines and other structures;
- ☐ Identification of design criteria relative to operability and survivability for design earthquakes;
- ☐ Identification and development of appropriate structures for earthquake response.

As we will describe further in this text, the zonation and related criteria work was largely done by Bruce Bolt; the structural response work was performed by Nathan Newmark and W.J. Hall.

The seismic design, as we will show, impacted the design of certain facilities and pipeline segments very heavily, particularly when contrasted with similar designs elsewhere. In addition, seismic design integrity has been maintained in an integrated program consisting of design control, configuration management, seismic housekeeping and earthquake response planning, as will be further described.

For all of that planning, TAPS never experienced an earthquake approaching design levels until November 2002, when an earthquake occurred along the Denali Fault of magnitude 7.9. This closely approached the Design Contingency Earthquake level – a term that will be explained further– of magnitude 8.0 in the region of the event.

This report will explore the design criteria applicable to TAPS, with special mention of the Denali Fault area; it will discuss how the outcomes of the event related to those design parameters; and it will relate the experiences of that earthquake, and the lessons learned, to the actions taken since then.

Design Criteria Development History

The seismic design criteria for the Trans Alaska Pipeline were developed in two major phases, which actually were performed in parallel. The first phase involved characterizing the seismicity of the pipeline; the second involved development of the engineering response characteristics and design procedures.

Work on these criteria began in 1969, a little over a year after announcement of the major discovery in Prudhoe Bay. In April of that year, under the new administration of President Richard Nixon, the U.S. Department of the Interior[2] set up a North Slope task force to assure that development of oil resources would protect Native rights, public lands and the environment.[3] Less than a month later, in May 1969, President Nixon directed the establishment of an expanded task force spanning federal departments but led by the Interior Department. The task force soon identified the need for a comprehensive examination of engineering criteria applicable to the Alaskan environment, which were largely absent from initial oil company planning for North Slope and TAPS development.

With respect to pipeline construction, oil company engineers were familiar with the ASME B31.3 and B31.4 codes, which for most pipelines formed the governing requirements. There were no codified civil engineering criteria in 1969 to address key aspects of design in this case including stable placement of the pipeline in permafrost, and seismic design. In 1969, the industry showed little interest in cooperating with the government to identify and address these issues, and generally argued that design and construction practices used in the lower 48 would be adequate.[4]

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[2] The Secretary of the Interior was Walter J. Hickel, who had been Governor of Alaska prior to his nomination and confirmation, after protracted controversy. Hickel had been an outspoken proponent of North Slope development, and the work of the task force was a high priority for his administration of the department.

[3] Coates *(Ibid.)*

[4] Coates *(Ibid.)* quotes Henry Coulter of USGS, in 1981 testimony before the Federal Energy Regulatory Committee; Coulter recounted a 1969 hearing in Fairbanks wherein oil company officials presented plans for conventional burial only. He stated, "TAPS simply planned to dig a ditch from one end of Alaska to the other and bury the pipeline in it, notwithstanding the existence of permafrost."

To address these criteria, a subgroup to the federal task force, known as the Menlo Park Working Group, was established at the Alaska branch of the U.S. Geological Survey (USGS) in Menlo Park, California in 1969. This group's purpose was to examine the "technical aspects of the proposed pipeline" which would primarily be civil oriented.

Specific to seismic design, the USGS invested in additional characterization of the geological hazards and seismicity of the pipeline route. Particular interest was focused on the Denali Fault. This fault was well known to geologists, though not well characterized. It had previously been mapped in 1941-42 and became an area of concern, because a fault crossing was unavoidable. Lloyd Cluff*, et al.* wrote: "Although the Denali Fault had geomorphic evidence indicating it was as dangerous as the San Andreas, the last major displacement apparently predated 1800, strongly suggesting significant strain accumulation since the last earthquake."[5] It is now understood that a M 7.2 to 7.4 event had occurred along the fault in 1912,[6] but concerns were sufficient to warrant establishment of a temporary seismographic network, which ultimately showed only four of 33 microearthquakes detected along the fault trend line.[7]

Working under the Menlo Park subgroup, a USGS team (Page, Boore, Joyner and Coulter), published the final results as Geological Survey Circular 672, *Ground Motion Values for Use in the Seismic Design of the Trans-Alaska Pipeline System* in 1972. By the time of publication, the U.S. Department of the Interior had already put together a set of draft Stipulations to its draft Agreement and Grant of Right of Way taking account of the Circular 672 results.[8] In fact, the circular quotes the draft Stipulation requirements, which included zonation of the pipeline and establishment of design Richter intensity levels appropriate to each zone.

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[5] Cluff, Page, Slemmons and Crouse: "Seismic Hazard Exposure for the Trans-Alaska Pipeline," *Advancing Mitigation Technologies and Disaster Response for Lifeline Systems: Proceedings of the Sixth U.S. Conference and Workshop on Lifeline Earthquake Engineering*, August 10-13, 2003, Long Beach, California (James E. Beaver, editor). Washington, D.C.: ASCE Press, 2003.
, Long Beach, CA, American Society of Civil Engineers, August 2003. Available at: http://www.alyeska-pipe.com/Inthenews/techpapers/1-Seismic%20Criteria%20for%20TAPS.pdf (accessed April 3, 2009).

[6] Carver, Pflaker, Metz, Cluff, Slemmons, Johnson, Roddick and Sorensen: "Surface Rupture on the Denali Fault Interpreted during the 1912 Delta River M_w 7.2-7.4 Earthquake: Implications for the 2002 Denali Fault Earthquake Slip Distribution." *Bulletin of the Seismological Society of America,* Vol. 94, No. 6B, pp. S58-S71. December 2004.

[7] Cluff, Page, Slemmons and Crouse.

[8] "Stipulations for Proposed Trans-Alaska Pipeline System," Federal Task Force on Alaskan Oil Development, U.S. Department of the Interior. *Final Environmental Impact Statement.* Washington, D.C., 1972.

As the technical work of the Menlo Park subgroup was advancing, the TAPS consortium (consisting of seven owner organizations) organized a new subsidiary, Alyeska Pipeline Service Company (APSC). The new subsidiary's first mission was a large one: it was to complete planning, right of way acquisition, contracting and engineering for the project. Completion of design criteria and engineering design procedures was a large part of that effort, and was in fact required by agencies for receipt of a permit. Moreover, the permits for the pipeline were under serious legal challenge; challenges from Alaskan Natives were resolved with the passage of the Alaska Native Claims Settlement Act (ANCSA) in 1971 but environmental lawsuits persisted until quashed legally by Congress and the President in 1973. The intensity of those challenges assured that APSC had to produce credible engineering criteria. In effect, this required APSC to meet the requirements developed primarily by the Menlo Park Working Group. In a cultural shift, the owner companies had to accede to these new requirements, to find ways to cooperate with the Menlo Park task force and to collaborate with them in order to assure that they would have a voice in the ultimate requirements.

Accordingly, the TAPS effort included a validation phase for characterizing seismicity along the TAPS route. This was completed by the late Professor Bruce Alan Bolt (University of California Berkeley) in March 1972.

Bolt's work appeared to further refine that of the Menlo Park working group, which (based on references to his work in Circular 672) they were well aware of. In general, Bolt concluded that the design earthquake levels along the pipeline could be reduced from those specified in the Stipulations. He also disaggregated the zone that included the Denali Fault into several subzones, one of which was in the near vicinity of the fault itself where a magnitude 8.0 to 8.5 earthquake was likely. Bolt defined this zone to be 55 km in length. Elsewhere, within this segment, mean peak acceleration was assessed by Bolt as 0.40g based on a Denali rupture.

It is not clear whether APSC hoped Bolt's efforts could lead to a lowering of the design thresholds or not; in any event, no change was forthcoming. However, Bolt's work was incorporated, in part, into the second major phase of TAPS work, which was the development of engineering design procedures. This was conducted by Nathan Newmark and William J. Hall of the University of Illinois. In fact, the Menlo Park group deferred to Newmark and Hall, whose work they were aware of in 1972, but whose procedures was not published until 1973.

The involvement of Newmark and Hall on behalf of the TAPS owners may be interpreted as a triumph, a concession by industry, a recognition by the industry of the primacy of their approach, or all three. In fact, the USGS report of 1972 cited, as a primary reference, the 1969 paper by Newmark and Hall laying out a method for determining envelope response spectra. In retaining Newmark and Hall, the TAPS owners (acting through its agent, Alyeska Pipeline Service Company) recognized that this method would become the basis of design.

As described later in the text, Newmark and Hall defined the basis for structural design of the pipeline and auxiliary facilities. Among their accomplishments were the definitions of design and operating earthquakes by zone, and identification of response spectra for the pipeline and other structures.

These design criteria were ultimately promulgated into the development of structural design procedures and details. Some design procedures were revised only in the early part of the current decade, following an analysis that showed current International Building Code procedures – relying largely on ASCE 7 – now yielded results similar to those of the older design procedures. Older loading and code criteria were not as conservative, and codes had evolved to a result compatible with the work of Newmark and Hall in the early 1970s.

Fundamental Seismic Design Criteria: Ground Accelerations and Durations

As noted earlier, the TAPS Stipulations focused on oil spill prevention as a driving factor behind seismic design. To that end, spillage from the pipeline, tanks, marine terminal berths, facility piping, and vessels were all considered targets of prevention.

Even though not explicitly addressed in the Stipulations, there were three other key considerations: life safety, minimization of damage to facilities, and minimization of disruption to pipeline operations. These goals complemented the goal of oil spill prevention; however, it was recognized early that seismic intensity thresholds might pertain to the different goals.

Establishing the basis for seismic design requires identification of design event characteristics, and the response characteristics associated with those designs.

The design event characteristics of predominant interest are ground accelerations and durations. These design events vary geographically as a function of regional geology (tectonics).

Key parameters relevant to the TAPS system included:

- ☐ The probability of earthquakes of varying magnitudes and varying distances from the pipeline route
- ☐ Maximum expected acceleration on firm ground, which had to be derived from the seismicity record and geology
- ☐ Duration of strong motion

As discussed earlier, studies by the USGS established "design earthquake" – later called "design contingency earthquake" - magnitudes that were broadly applied to each of five seismic zones along the pipeline route. These magnitudes were as follows:

Zone	Richter Magnitude
Prudhoe Bay to 67 north	5.5
67 north to Donnelly Dome	7.5
Donnelly Dome to Paxson	8.0
Paxson to Willow Lake	7.0
Willow Lake to Valdez	8.5

It may be useful to discuss what the meaning of such criteria would be. These Richter magnitudes reflected earthquakes with a return interval of up to 500 years which was a period roughly an order of magnitude higher than the expected life of the Trans Alaska Pipeline.[9] It follows that for each of the five regional zones, the structures should be designed for seismic forces resulting from the design earthquakes. This would effectively mean either greater force resistance or greater flexibility to movement in areas where the Richter magnitude would be higher.

The reference to Richter magnitude is of considerable interest. At the time the original design criteria were written, there was no other generally accepted standard. In today's practice, Richter magnitudes are now known as local magnitudes, which lead to "saturation" at magnitude 7.[10]   In addition, the Richter magnitude actually exhibits "nonlinear" behavior with regard to the logarithmic magnitude scale at about magnitude 5. That is, it has been shown that the Richter scale does not adequately represent events with greater energy release For that reason, the moment magnitude scale has superseded the Richter scale as a generally recognized energy scale for magnitudes exceeding 7.5, and the surface wave magnitude scale has superseded Richter for magnitudes between 5 and 7.5.[11]

A fair question may be what the modern equivalent earthquake magnitudes should be, and whether that should change the design basis. As a point of reference, the Great Alaskan Earthquake of 1964 (also known as the Good Friday Earthquake) was originally characterized as 8.4 on the Richter scale, but is now characterized as 9.2 on the moment magnitude scale. However, this question was extinguished when, in the early part of this decade, the Grant and Lease of Right of Way was amended to reference moment magnitudes in lieu of Richter magnitudes.

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[9] The original TAPS design criteria were written under the assumption that the pipeline would have a 30 year economic life. The original Grant and Lease were therefore for 30 years, beginning in 1974 and expiring in 2004. The Grant and Lease was renewed in late 2002.

[10] Steven L. Kramer, *Geotechnical Earthquake Engineering.* Upper Saddle River, N.J.: Prentice-Hall, 1996. Figure 2.29 on p. 49 includes a graph of saturation for the Richter and other scales with respect to the moment magnitude scale.

[11] *Ibid.,* p.50. Kramer cites Bolt on this matter.

Design Ground Motions

The term "Design Contingency Earthquake" (DCE) is similar to the concept embedded in "Maximum Considered Earthquake" (MCE) as codified in the 2006 International Building Code. The DCE would be a rare intense quake, and would result in limited damage, but "no spills, structural damage or loss of function."[12] This was in contrast with the Design Operating Earthquake (DOE), a designation not required by the Stipulations, representing lower intensity earthquakes with a 100 or 200 year recurrence interval.

Accelerations and ground shears corresponding to the DCE intensities along TAPS are as follows:

Richter Zone	Effective Peak Acceleration for structures, EPA (g)	Spectral Acceleration S_a (g)	Free-field Acceleration (g)	Free field peak velocity (in/sec)	Structure peak velocity (in/sec)
8.5	0.33	0.86	0.60	29	16
8.0	0.33	0.86	0.60	29	16
7.5	0.22	0.57	0.45	22	11
7.0	0.15	0.39	0.30	14	7
5.5	0.10	0.26	0.12	6	5

It is noted that these are horizontal velocities and accelerations. Design vertical acceleration is 2/3 of the horizontal acceleration for all zones.

In a DOE, the pipeline would be expected to continue operating without interruption. DOE levels were not specified in terms of Richter magnitude; rather, for each zone, accelerations were taken as ½ of the structural design acceleration arising from DCEs and were plotted with 2% of critical damping[13] on the design response spectra sheets discussed below. (DCEs, by contrast, were plotted at full design acceleration with 7% damping.)[14]

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[12] Mark Anderson and Doug Nyman, "TAPS Design Criteria and Specifications" (PowerPoint presentation, Anchorage, Alaska, June 26, 2006)

[13] Critical damping is described by the USGS as the "least value of damping for which the damping prevents oscillation. Any particular damping value we can express as a percentage of the critical damping value. Because

Response Spectra and Structural Design (Newmark and Hall)

Having defined the Richter magnitude associated with each of five regional zones, it remained to determine what maximum accelerations (and therefore what maximum inertial forces per d'Alembert's equation) would result from seismic events of those magnitudes. Secondly, there was the question of what response would be induced in a structure, given structural damping. Determination of this was the essence of seismic design for the structures.

Although the mainline pipe is the primary structure of interest, it is important to understand that many other structures require seismic design consideration. Among the most critical structures were the crude oil tanks, particularly the storage tanks located at the Valdez Marine Terminal. The potential for failure of tanks due to sloshing, and subsequent "elephant foot" crushing, was well understood when TAPS was under design. However, many other structures – bridges, buildings, retaining walls, containment dikes – required special consideration as well using essentially the same criteria as used for the mainline pipe. In addition, marine structures (i.e., berths) were designed to withstand tsunami and seiche wave run-up conditions.

To assist in the structural design, Newmark developed a set of design spectra for all DCE magnitudes. These are plotted on logarithmic tripartite charts which allows four axes to ge read (the horizontal axis is undamped natural period in seconds, the vertical is pseudo relative velocity in ft/sec; the diagonal axes are displacement (ft) and acceleration (g)). These

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spectral accelerations are used to represent the effect of earthquake ground motions on buildings, the damping used in the calculation of spectral acceleration should correspond to the damping typically experienced in buildings for which earthquake design is used. The building codes assume that 5 percent of critical damping is a reasonable value to approximate the damping of buildings for which earthquake-resistant design is intended. Hence, the spectral accelerations given in the USGS hazard maps at this NSHM site are also 5 percent of critical damping." http://earthquake.usgs.gov/research/hazmaps/haz101/faq/parm10.php (accessed April 22, 2009).

[14] "Newmark Standard Design Spectra," Appendix C of Appendix A-3.1080 *Summary Report, Design Criteria and Stress Analysis for the Trans Alaska Pipeline* (1971).

spectra are developed not only for earthquake magnitude but for particulate structure affecting subsoil amplification.[15]

Geotechnical Issues: Fault Displacements and Slope Failures

The pipeline, and all supporting structures, needed to be designed to withstand the effects of ground acceleration and, at the same time, permanent ground deformation.

In its traverse across Alaska, the Trans-Alaska Pipeline crosses three major known faults that were known at the time of construction. These are the Denali Fault, the McGinnis Glacier fault, and the Donnelly Dome fault (see Figure 1). Other faults exist, and some have been identified since the design period. Where options existed, the alignment was chosen to avoid areas where large ground deformation could occur.

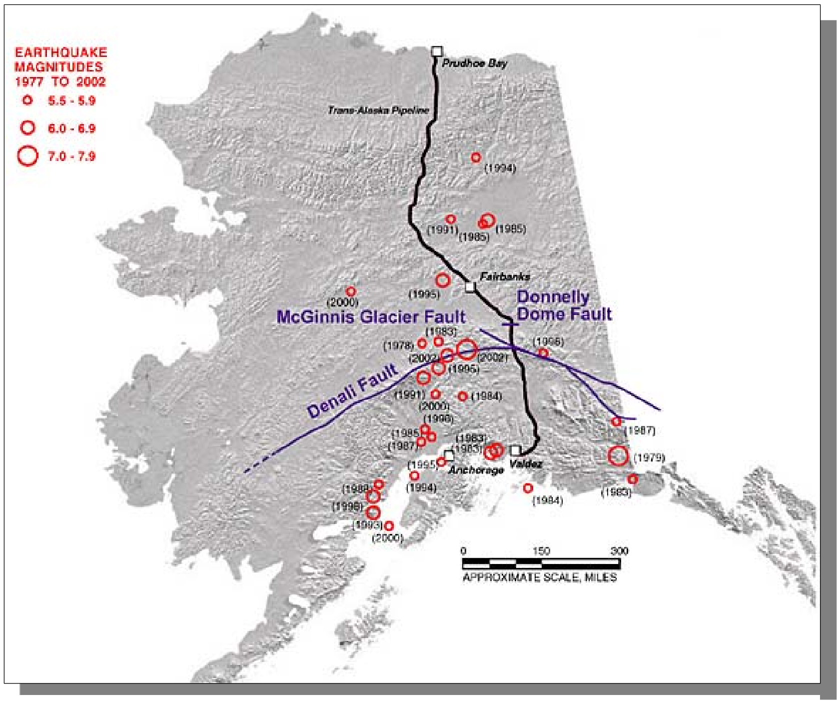

Figure 1 - Location of Faults and Major Earthquakes near TAPS

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[15] Type I conditions are for "hard soils": competent rock or permafrost on rock. Type II conditions are essentially competent soils atop rock or permafrost or vice versa. Type III indicates pocketed soft or broad moderately competent soils atop hard soils rock or permafrost). Type IV indicates soft soils atop competent soils, rock or permafrost. For each of these conditions, Newmark identified high frequency break points at 2% critical damping; he also identified the 7% upper break frequency and the ground acceleration-intercept slope and location.

At fault crossings, it is understood that ground deformation is anticipated, and the degree of deformation expected is important to understand.

Of particular interest is the question of uncharacterized faults. Where the pipeline is buried, it is possible that differential displacement of the ground could lead to rupture. This has happened in other earthquake, for instance, for pipelines (gas, water or sewer) at the interface of slide zones in other earthquakes. (This happened, for example, in Anchorage in the 1964 Great Alaskan Earthquake.) The possibility of such movements for buried TAPS piping was studied by Newmark, who found that "potential fault motions of 10 feet or less can be crossed nearly at right angles, subject to…restrictions [on depth of cover, to be limited to 3 foot with special precautions if grade X-70 material is used]."

The Denali Fault proved to be of greatest interest to both USGS and to Bolt, performing an independent analysis on behalf of TAPS. Bolt stated the following:[16]

> There is only one known seismically active fault which occurs within 50 km of the pipeline. This is the major strike-slip Denali fault which crosses the pipeline near 63° 15' N. The geological evidence is such that it is prudent to assume that a magnitude 8 to 8-½ earthquake (similar, e.g., to the 1906 San Francisco shock) may occur on this fault near the pipeline during its lifetime.
>
> The Denali fault zone, for this broad classification, is no more than a few km wide. However, there are geological reasons (e.g., mapped thrust faults 5 to 10 km to the south) and seismological reasons to define segments about 20 km in extent on each side of the Denali fault for a uniform seismic evaluation…In this region, the likely ground accelerations on firm ground are greater than at any other segment of the [Trans-Alaska Pipeline] route.

To accommodate potential ground movement, a special fault crossing zone was constructed (described further below). The special configuration is 2400 feet long, and is designed to envelope the 1900 foot crossing zone identified by geological work. This is characterized by grade beams throughout the length of the zone, with anchors placed on each end. Reportedly, this was the first time that such a special fault crossing zone had ever been

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[16] Bruce Bolt, Appendix A of Appendix A-3.1080 *Summary Report, Design Criteria and Stress Analysis for the Trans Alaska Pipeline* (1971).

constructed on a pipeline; conventionally, all pipeline fault crossings had been buried with shallow, sloped walls with loose backfill.[17]

Uncertainties in the location of the actual fault crossing caused it to be characterized to that width. With the 1900 foot (575 m) and additional 250 foot (75 m) buffer on each side, TAPS designers believed the design to be conservative.

The Denali Fault segment was designed to accommodate large deformations: 20 foot (6 m) horizontal slip and 5 foot (1.5 m) vertical slip. This was done using a different design concept than used elsewhere. Instead of being designed with a pile support system, the pipeline was placed aboveground atop long and low sleeper-style grade beams embedded and anchored in gravel berms.[18] This design both allows large displacements and – in the event that actual displacement exceeds the design – its low-to-the-ground sleepers assures that damage to the pipeline will be modest should the displacement overrun the ends of sleepers.

The Denali Fault trends northwest, and was characterized in original mapping crossing the pipeline at about a 61.5 degree angle.[19] The predominant fault movement is right lateral, putting the pipeline in compression in a seismic event. Relative to pipeline orientation, the design displacement components are reported to be 9.5 feet (2.9 m) longitudinal compression, 17.8 feet (5.4 m) transverse, and 5 feet (1.5 m) vertical.[20]

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[17] Johnson, Metz and Hackney: "Assessment of the Below-Ground Trans-Alaska Pipeline Following the Magnitude 7.9 Denali Fault Earthquake," *Advancing Mitigation Technologies and Disaster Response for Lifeline Systems (TCLEE Monograph No. 25). Proceedings of 6th U.S. Conference and Workshop on Lifeline Earthquake Engineering Long Beach, California, USA,* August 2003.

[18] A good description, in "Trans-Alaska Pipeline System Performance in the M7.9 Denali Fault Earthquake" by Honegger, et al. is as follows: "At the Denali fault crossing, the pipeline is supported on 33 steel box beams and concrete beams set on-grade, at approximately 18-m intervals over a distance of 579 m. The beams are approximately 12 m long [and] were sized and arranged to accommodate fault slip." Original article was in *Earthquake Spectra,* Volume 20, Issue 3, pp. 707-738 (August 2004).

[19] The fault crossing zone is mapped at a bearing of N55°W and the pipeline alignment trends toward a N 6°32'E bearing.

[20] Honegger, et al., *Ibid.*

Earthquake Notification and Response Planning

Alyeska Pipeline Service Company has a well developed operating procedure for seismic events. This procedure has evolved over the years, and is currently strengthened by its linkage to the statewide earthquake monitoring system. In fact, APSC's system of Digital Strong Motion Accelerometer (DSMA) devices reported only into the company's System Control and Data Acquisition (SCADA) system prior to 2008. This system has been updated and is now maintained and operated by the University of Alaska Fairbanks under contract with APSC, but still reports into the SCADA system. A further discussion of this is located at the end of this paper.

The system is set up based on Acceleration Thresholds, and specifically on Acceleration Threshold Exceedance (ATE) alarms defined into the system logic.[21] These ATEs are set up in three levels (low, medium and high); if a medium or high level ATE is received, the Auto Controls Logic in the pipeline computer control system will automatically shut down the pipeline after 10 minutes. There is a SEISMIC ACKNOWLEDGE button which enables a human controller at the Operations Control Center to stop the timer; he or she may decide either to shut down immediately or to continue to monitor the pipeline.

It is noteworthy that it is expected that the OCC operator will press the seismic acknowledge button and then take steps to determine what the next course of action will be. Continuing to run the pipeline in the short term may be considered an advantage, in that it enables the leak detection system to continue functioning as normal. A large bore cut will be immediately detectable using the deviation alarm functionality, and other large leaks may be detected quickly as well. The automatic shutdown functionality exists in the event that the operator became disabled as a result of a severe earthquake and was rendered unable to function.[22]

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[21] The description is taken largely from Alyeska Pipeline Service Company Operations Control Center Department Operating Procedure No. OCC-13.02-SR, "Known Seismic Events (Emergency Operating Procedure)," Revision 1, 12/14/08.

[22] Personal conversation with Jim Roddick, Alyeska Seismic Steward, April 27, 2009.

Because of the tie-in to the statewide system, EQRMS reports could, in principle, be generated for events detected by the statewide strong motion accelerometer network that do not trigger a medium or high level ATE alarm, but which are predicted to cause strong motions somewhere on the pipeline route. This secondary system is the "Earthquake Detection" (EQD) alarm system, which is received as a status bit change resulting from UAF's processing of data from multiple stations in the network. Because of the large integrative process requirements, the EQD alarm will be received 3 to 6 minutes after the ATE alarm.

Post earthquake reconnaissance directions are now triggered by the Earthquake Response Monitoring System (EQRMS), which provide directives and priorities for inspecting facilities that could be subject to damage. These reports directly result from data generated by the UAF processing, based on the initial "solution" mapping ground shaking intensity in the region. This solution is improved by further processing over time by the UAF Seismology Department (usually resulting in event downgrading, as a practical matter) and the corresponding reconnaissance directions may also be refined as well.

Denali Fault Earthquake

In preparing this report, the author has made no attempt to research all the earthquakes that the TAPS system has withstood in the 32 years since pipeline operations began. Given the level of seismic activity in Alaska, particularly along the southerly segment of the pipeline, there must have been hundreds to thousands of earthquakes. As is always the case, the vast majority of these events are imperceptible or, at most, minor.

As mentioned earlier, only one event has approached the design criteria of TAPS. This was the Denali Fault earthquake of November 2002. This had a magnitude of 7.9, slightly below the design Richter magnitude applicable to the region. It is the only event to date in which ground deformation occurred in a significant manner, altering the placement of TAPS.

The general pattern of the aboveground pipe throughout the TAPS system is a "zee" configuration. This is a configuration with a regular series of alternating side-bends, with anchors in a given segment to restrain axial movement, and intermediate supports to accommodate limited horizontal sliding (e.g., due to thermal expansion) and gravity support. Throughout the system, except at two fault crossing (Denali and Donnelly Dome faults) the intermediate supports use pile (vertical support member a/k/a VSM) supported crossbeams; the assemblies.

In the actual event of November 3, 2002, the horizontal displacement varied along the Denali Fault complex. The maximum displacement of 9 meters (almost 30 feet) was reported near Mentasta Lake on the east end of the rupture zone. On the west end of the rupture zone, the displacement was around 1 meter. The location of the pipeline crossing turned out to be about 2/3 of the way from the east to west end of the rupture zone[23] (i.e., significantly closer to the minimum displacement end); accordingly, the degree of displacement was much less at the pipeline crossing. A photograph of the nearby Richardson Highway crossing appears to show that the local horizontal displacement was about half of a lane width (2 to 2.5 meters was reported).[24] Local to the pipeline crossing, which is nearby, the displacement of the fault was reported to be 5.42 meters (17.8 feet).[25] Therefore, the amount of slip appears to have been well within the design envelope. (It is noteworthy, however, that had the displacement matched that of Mentasta for the same event, this would have been well outside design constraints.)

As discussed above, the fault crossing zone was originally set at a length of 1900 feet because uncertainties in geological evidence made it difficult to pinpoint the exact crossing zone. When the November 3 quake occurred, the actual fault zone became exposed. It was confined to a 60 foot segment almost at the southern end of the design fault zone.

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[23] D. Eberhart-Phillips, *et al.,* "The 2002 Denali Fault Earthquake in Alaska: A Large Magnitude, Slip-Partitioned Event," *Science* 300:1113 (2003).

[24] The photograph is viewable at: http://neic.usgs.gov/neis/eq_depot/2002/eq_021103/alaska_map4.html (accessed April 13, 2009).

[25] William J. Hall, *et al.*, "Performance of the Trans-Alaska Pipeline in the November 3, 2002 Denali Fault Earthquake," *Advancing Mitigation Technologies and Disaster Response for Lifeline Systems: Proceedings of the Sixth U.S. Conference and Workshop on Lifeline Earthquake Engineering*, August 10-13, 2003, Long Beach, California (James E. Beaver, editor). Washington, D.C.: ASCE Press, 2003.

Subsequent investigation showed that past events had also occurred within the same location, and future fault movement was expected to occur there as well.[26] The bearing of the actual fault was found to be essentially identical to the bearing characterized during TAPS planning.

Pipeline Performance

Because of the orientation of the pipeline relative to the fault, the 18 foot (5.5 meter) fault displacement resulted in a net compressive displacement of about 11.5 feet (3.5 meters) in the fault zone. Because of the close proximity of the actual fault rupture to the southern terminus of the fault zone (about 120 feet, or 36 m), and therefore to the southerly anchor (about 370 feet, equaling 112 m the conventional above ground section was subject to violent near-field shaking, exceeding anything that had been anticipated. The ground motions resulted in the following:

- The pipeline was predictably displaced toward the outside of some of the bends, but the final configuration within the fault zone stayed within the range of the sleeper beams. Within the fault crossing zone, there was shifting of both the grade beams and pipeline. The grade beams were displaced east north of the fault, up to 9 feet (2.7 m), and west south of the fault (up to almost 7 feet (2.1 m)).[27] Minimum movement occurred in the grade beam straddling the fault. The pipeline was generally displaced slightly west.
- The net compressive displacement resulted in the pipeline assuming a "bowed" shape in a formerly straight segment. (See Figures 2 and 3 below for a before and after comparison illustrating this.)

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[26] Michael Baker, Inc. for Alyeska Pipeline Service Company: *Denali Fault Earthquake Repairs Preliminary Design Engineering Report Volume I*, May 2004.

[27] Cluff, *et a*l., *Report of the Alyeska Fault Evaluation Team 2003* (report prepared for Alyeska Pipeline Service Company).

Figure 2 – Original pre-earthquake alignment view of Denali Fault crossing, looking south

Figure 3 – Post-earthquake alignment from similar vantage point, looking south, showing compression bending and displacement

- The relative displacements caused shoe-supports to travel to near the edge of the crossbeams. Post earthquake analysis showed that four crossbeams had less than 5 feet of travel remaining to the edge of the crossbeam, due to displacement of both the pipe and crossbeam (about 20 to 25 feet (6 to 7.5 m) of "travel" from original position to end position was calculated relative to original construction). Thus, a subsequent seismic event of comparable intensity could be expected to result in the pipeline's travel off the crossbeam.[28]

- Damage was noted in areas outside the fault crossing zone. Most notably, as shown in Figure 4 below) two adjacent supports were completely separated (knocked off) from the VSM casings, probably due to the side-to-side violent impact of the pipe against the piles, which caused the piles to deform from the vertical and assume an outward lean. (Because the crossbeams are fixed lengths, this pile spreading action caused them to fall.) Given the fact that a design criterion had been assurance that the pipe would not be overstressed with loss of two adjacent supports, this tested the performance of the pipeline against the maximum span criteria – a more severe test than was ever anticipated.

Figure 4 – Loss of two consecutive crossbeams due to near field seismicity just south of Denali Fault

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[28] Specifically, the Michael Baker report *Denali Fault Crossing Post Earthquake Analysis Engineering Report* (September 2003) states: "Now, assuming that future faulting and dynamic shaking will be proportional to the November 3rd [2002] event, a total additional 2 feet of surface faulting would cause the crossbeam at support 16 to move 1.2 feet east, [and] the pipe to move an additional 1.8 feet west…Thus, this analysis indicates that the pipeline in its current condition can withstand an additional 2 feet of displacement [added to "shakedown" displacement] without the pipeline shoes displacing laterally beyond the end of the crossbeam at any support."

- Also outside the fault crossing zone, several shoes were vertically separated from their supporting crossbeams, some of which remained intact and others of which fell to the ground. The pipe was therefore "dangling" unsupported at these bents (Figure 5). Several anchors were "tripped" (traveled to or past their stop limits); piles were deformed from the vertical and bent due to violent sidesway pipe impact (Figure 6).

Figure 5 – Loss of Crossbeam and Shoe

Figure 6 – Vertical Support Member (VSM) outward bending due to sidesway impact

- At the first VSM bent south of the pipeline fault zone, the pipeline support shoe underwent severe damage, with several components nearly sheared off, and others buckled. This was probably due mostly to violent dynamic shaking in the vertical direction.

Figure 7 – Collapsed Shoe at VSM Bent

- In high groundwater areas of floodplains near the fault zone, there were liquefaction events resulting in sand boils, surface cracking and lateral spread of fill over the pipeline. This was in areas with high groundwater and slight (<2%) gradients.[29] At one remote gate valve (RGV 91) the sand boils appeared near the valve, with apparent settlement the valve and pipeline, possible flotation of the propane tanks, and lateral bracing damage to the shelter housing the energy converter unit, batteries and communications/control equipment.

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[29] Johnson, Metz and Hackney: "Assessment of the Below-Ground Trans-Alaska Pipeline Following the Magnitude 7.9 Denali Fault Earthquake," *Advancing Mitigation Technologies and Disaster Response for Lifeline Systems (TCLEE Monograph No. 25). Proceedings of 6th U.S. Conference and Workshop on Lifeline Earthquake Engineering Long Beach, California, USA,* August 2003. Available at: http://www.alyeska-pipeline.com/InTheNews/techpapers/4-TAPS%20BelowGround%20Denali%20EQ.pdf (accessed March 20, 2009).

Figure 7 – Liquefaction at a Remote Gate Valve site (RGV 91)

The significant damage to the aboveground system was summarized in a report as follows:

> In summary, there were eight locations that experienced loss of support (five losses of crossbeams and shoes, and three loss of shoes), nine anchor slide assemblies that tripped, and six additional locations with connection bolt failures. Damage to the aboveground support insulation modules, ranging from minor cracking to major crushing, was noted throughout the area, typically decreasing in severity away from the fault zone.[30]

Response of Pipeline Operator

At the time of the Denali Fault earthquake, TAPS had been operating for 25 years and 4 months. During that time, Alyeska Pipeline Service Company responded to multiple

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[30] Michael Baker, Inc.: *Post-Earthquake Assessment Engineering Report*, prepared for Alyeska Pipeline Service Company, December 2002.

emergency events, notably oil spills, with a reasonably well defined protocol. Since the early 1990s, all responses have followed an Incident Command System (ICS) model, patterned after wildfire response protocols developed in California.

The shaking began at 1:12 PM, as recorded on Alyeska's Earthquake Monitoring System (EMS). The shaking was very intense enough at Pump Station 10 (PS-10) – located only 3 km from the surface rupture and 85 km from the epicenter.[31] In fact, seismic alarms were generated in six stations from Pump Stations 7 through 12, a distance of 321 miles (517 km).[32] In addition, the event could be felt in Operations Control Center (OCC) in Valdez. The measured peak acceleration at PS-10 was 0.337 g horizontal and 0.238 g vertical (compared with free-field design acceleration values of 0.600 g horizontal and 0.400 g vertical). It is noted that these measurements are bandpass filtered at 0.1 Hz. A subsequent USGS analysis indicated that the actual maximum peak velocity may have been up to 50% higher than that calculated from accelerograms (i.e., 170 cm/sec as opposed to the calculated value of 114 cm/sec).[33]

This event triggered both a shutdown and employment of the ICS system, followed by repair work and subsequent engineering analysis.

The EMS system was reported to have "initiated an auto-shutdown" of the pipeline in a press release, but the actual shutdown was initiated under OCC control 38 minutes after the event[34] after pipeline management was contacted for direction.[35] Because the event occurred

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[31] As noted below, the free field acceleration values were likely approached but not exceeded at PS-10. There was no notable damage at this pump station facility, other than toppled cabinets found after the fact. Damage may have been significantly greater had the pump station been operational at the time of the event (so that the crude oil, turbine fuel and residuum tanks and various process vessels would have been partially filled). However, the station had been "ramped down" (mothballed) in 1996, because its pumping capacity was no longer required due to declining throughput.

[32] Nyman, Johnson and Roach: "Trans-Alaska Pipeline Emergency Response and Recovery following the November 3, 2002 Denali Fault Earthquake." *Advancing Mitigation Technologies and Disaster Response for Lifeline Systems (TCLEE Monograph No. 25). Proceedings of 6th U.S. Conference and Workshop on Lifeline Earthquake Engineering Long Beach, California, USA,* August 2003

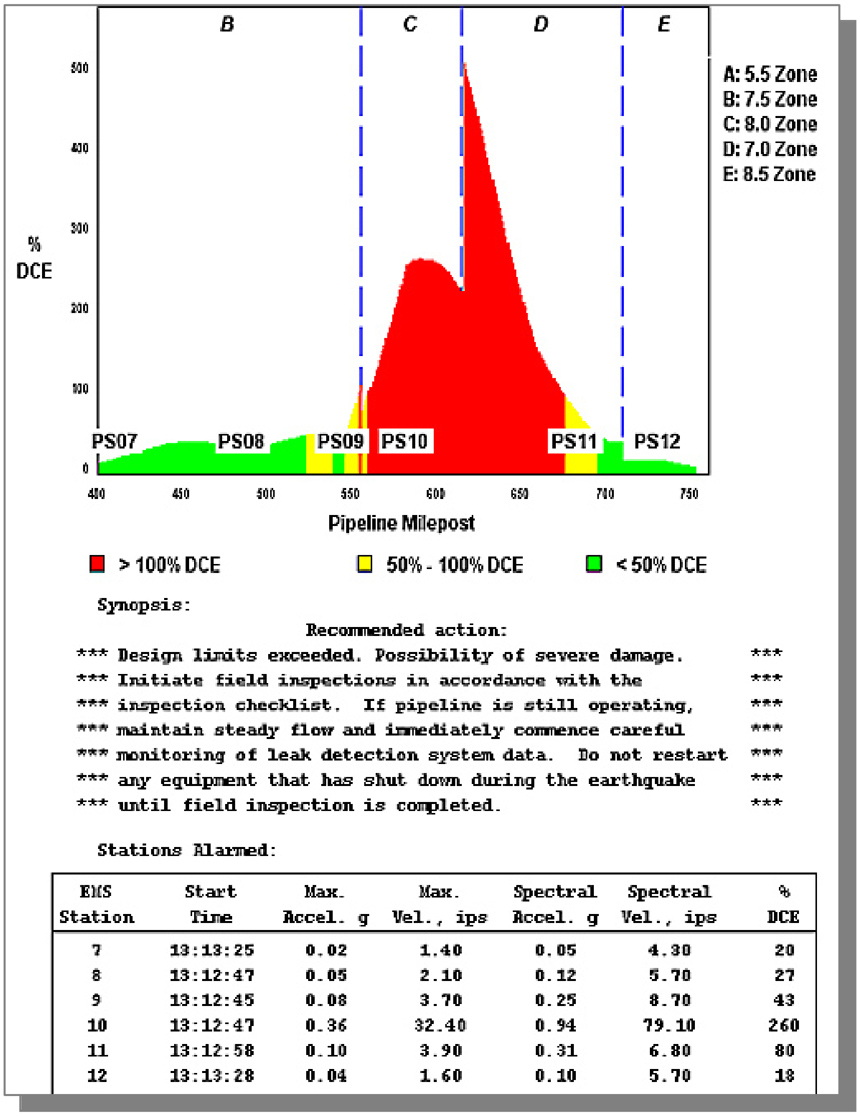
[33] Johnson, Metz and Hackney:

[34] http://www.alyeska-pipe.com/InTheNews/Newsbulletins/2002/bulletin1366.html (press release November 4, 2002). Accessed April 27, 2009.

[35] At the time of the event, every hour the pipeline was shut down was estimated to cost $1 MM in "lost" throughput. Source: Nyman, Johnson and Roach paper.

on a Sunday, managers were contacted at home and the directive was given to shut down the line pending a damage assessment.

That afternoon, an Incident Command System (ICS) organization was formed in the Fairbanks Emergency Operations Center (FEOC). Field personnel were dispatched to perform reconnaissance through a wide area. The guide to reconnaissance was a run of a software package called "DrQuake" which processed earthquake information within the TAPS DSMA system only. (At that time it was not tied into the UAF system.) The limited data available within the system caused the software to skew the damage somewhat south of the actual location. The output of DrQuake for this event is shown in the following figure:



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Synopsis:
                    Recommended action:
*** Design limits exceeded. Possibility of severe damage.     ***
*** Initiate field inspections in accordance with the         ***
*** inspection checklist.  If pipeline is still operating,    ***
*** maintain steady flow and immediately commence careful     ***
*** monitoring of leak detection system data.  Do not restart ***
*** any equipment that has shut down during the earthquake    ***
*** until field inspection is completed.                      ***

Stations Alarmed:
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EMS Station	Start Time	Max. Accel. g	Max. Vel., ips	Spectral Accel. g	Spectral Vel., ips	% DCE
7	13:13:25	0.02	1.40	0.05	4.30	20
8	13:12:47	0.05	2.10	0.12	5.70	27
9	13:12:45	0.08	3.70	0.25	8.70	43
10	13:12:47	0.36	32.40	0.94	79.10	260
11	13:12:58	0.10	3.90	0.31	6.80	80
12	13:13:28	0.04	1.60	0.10	5.70	18

Figure 8 – DrQuake output for Denali Fault event November 3, 2002

Reconnaissance crews were dispatched by ground and helicopter to determine, first, whether there were oil spills in progress. There were none. Had there been, the response would have turned immediately to oil spill containment. However, the helicopter based responders did find the gross damage in the vicinity of Pipeline Milepost (PLMP) 588, the immediate vicinity of the Denali Fault.

Eight teams of engineers and pipeline maintenance specialists were assembled and dispatched to assess damage.[36] These included several out of state earthquake experts, some of whom worked on the original TAPS design criteria. The crews followed the inspection protocol called out by DrQuake, but this was the first time that the inspection protocol had ever been required. DrQuake automatically created a list of 160 items, 95 of which had been evaluated by 6:30 PM the day after the quake.[37]

As it turned out, there were two problems: first, it proved difficult to coordinate field crews, due to:

- ❑ difficulties in handling the forms as designed at that time,
- ❑ communication difficulties to remote locations
- ❑ errors in the shake map generated by DrQuake which skewed the response map southward.

A form known as a Rapid Response Form was filled out as reconnaissance crews checked out various sites for damage.

As noted, there were no leaks in the pipeline. Although there was heavy damage to certain portions of the system (e.g., one collapsed shoe) and relatively light damage to other components, the pipeline itself was not compromised. That said, there was concern that aftershocks could cause further and preventable damage. The immediate priority was therefore to stabilize the pipe. To that end, temporary structures such as wood cribbing were placed to support "dangling" segments of pipe.

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[36] Alyeska News Bulletin 1368, November 4, 2002, 6:30 PM. Available at http://www.alyeska-pipe.com/InTheNews/Newsbulletins/2002/bulletin1368.html (accessed April 27, 2009).

[37] *Ibid.*

Figure 9 – Temporary cribbing under Trans Alaska Pipeline two days after event

In addition, there were exploratory investigations conducted in parallel with the repairs; for example, RGV 91 was excavated to assure that its integrity was intact. Soil gas testing was performed to ensure there were no leaks, and two line segments were reportedly "pressure tested."[38]

The assessment teams assigned priorities to repairs: Priority 1 tasks were those required prior to pipeline restart. These included the items discussed above (although it is noted that about 10% of the wood cribbing work was not deemed essential for restart). With the completion of that work, the pipeline was restarted at 8:23 AM on Wednesday, November 6, 2002 with reduced operations. Full production was reported on 4:11 PM that same day.[39]

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[38] Alyeska News Bulletin 1371, November 5, 2002. http://www.alyeska-pipe.com/InTheNews/Newsbulletins/2002/bulletin1371.html (accessed April 27, 2009).
[39] Alyeska News Bulletin 1374, November 7, 2002, http://www.alyeska-pipe.com/InTheNews/Newsbulletins/2002/bulletin1374.html (accessed April 27, 2009).

Running a curvature/deformation pig (in-line internal inspection device) was the final check on the integrity of the mainline pipe – assuring that the structural integrity of the pipe was not compromised. Although planning for the pig run began the day of the earthquake event, the actual run required pipeline restart. In fact, it was necessary to run five cleaning pigs to remove wax accumulation before the instrumented pig could be run. No pipeline damage – in terms of denting or increased strain – was recorded. In fact, the notable curvature changes were in the vicinity of RGV 91, and these were in the direction of reducing to a lower strain level. In the pipeline segment between Pump Stations 9 and 11 (encompassing the earthquake area), there had reportedly been 15 previously discovered pipeline dents and 18 other anomalous bending curvature locales; per the pig run, none was found to have changed after the event.[40]

On a longer term basis, there was a need to restore damaged components to a functional state. That is to say, wood cribbing was acceptable only as a temporary solution to compromised pipeline support, and there was a need to complete permanent repairs. The priority of such repairs needed to be assigned, in part, based on the concern that additional fault displacement could occur.

To identify priorities, Alyeska's Survey group collected shoe position data on November 13, 2002. An after the fact analysis stated the following:

> Because of the onslaught of winter, a decision was made during the early repair period to try to accommodate any further short-term fault movement by leaving the support beams in place and relocating the shoes on the pipe where necessary. This would allow additional longitudinal and lateral movement capacity. By consensus among geologists, it was decided that this was a major event and that it had released most if not all of the locked-in strain energy. The geologists expected no more than a 1.7 m displacement potential in the short term. This was believed to be an upper bound limit.. The allowable extents of future longitudinal shoe movements were estimated based on the least remaining amount of lateral shoe movement available on the grade beams…The final locations of the

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[40] Johnson, Metz and Hackney. Note: neither this account, nor the others found by the author, date the instrumented pig run. However, based on the fact that five cleaning pig runs were found to be necessary, and based on other operational constraints (notably, the need to avoid two pigs running at once in the same segment), it is the author's belief that the instrumented pig run would likely have been about 3 to 4 weeks after the event.

> shoes were then determined by adding the expected longitudinal movements to the post-earthquake locations for each shoe and verifying whether or not the shoe could still rest on the beam [while incorporated a 150 mm safety buffer]. A total of ten shoes were estimated to have less than 150 mm of remaining overhang after calculating the projected additional fault displacement. One shoe had less than 150 mm of overhang in its post-event position. All eleven of the target shoes were recentered on the pipeline.[41]

The high priority stabilization work was completed in late 2002, but completion of repairs could not reasonably be performed due to the onset of interior winter conditions.

Reanalysis and Final Repair

A key issue of interest following completion of the initial repair phase was what degree of additional movement would reasonably be expected.

The geological evidence suggested strongly that a seismic event of comparable intensity was extremely unlikely to occur again on the Denali Fault within the remaining lifetime of the Trans Alaska Pipeline (estimated to be 30 to 50 years at that time). An undated position paper by three prominent experts stated the following:

> Geologic data indicate a long-term average slip rate on the Denali fault of 8 to 20 mm/year. GPS data suggest 5 to 10 mm/yr. Although these slip rate values range widely, given a maximum displacement of 8.8 m on November 3, 2002, they indicate the displacement released strain that required at least 440 years to accumulate (at 20 mm/yr) and possibly as many as 1760 years (at 5 mm/yr). These slip rates indicate the likelihood of another displacement on this fault segment in the short term is virtually nil…We know of no short-term repeats of large strike-slip displacements on the same rupture segment, except for rare cases of relatively short overlaps and relatively small displacements at the ends of rupture segments. We judge that there is no urgency to restore the previous capacity of the pipeline to accommodate displacement on the Denali fault.[42]

This analysis gave rise to the question of design standards for reconstruction. Most fundamentally, there appeared to be engineering justification for reducing the design

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[41] Sorensen and Meyer, "Effect of the Denali Fault Rupture on the Trans-Alaska Pipeline." ." *Advancing Mitigation Technologies and Disaster Response for Lifeline Systems (TCLEE Monograph No. 25). Proceedings of 6th U.S. Conference and Workshop on Lifeline Earthquake Engineering Long Beach, California, USA,* August 2003. Available at http://www.alyeska-pipe.com/Inthenews/techpapers/2-TAPS%20Fault%20Crossing%20Denali%20EQ.pdf (accessed March 21, 2009).

[42] Lloyd Cluff, George Pflaker and David Slemmons: "Is There an Urgency to Restore the Pipeline's Denali Fault Displacement Capacity?" (undated).

earthquake level in the Donnelly Dome to Paxson area from magnitude 8.0 to something less. This reassessment would take advantage of time-dependent model for a probabilistic seismic hazard assessment (PSHA) which would very likely show the probability of recurrence of this quake within the life of the pipeline to be nearly zero. In the end, it was concluded that the costs of qualifying such a reduction in design standard, and in attempting to advance that reduced standard through the regulatory process, would exceed any benefits.[43] Accordingly, a final design engineering package was prepared by the consulting firm Michael Baker Jr. and issued in June 2004. Notable features of the final design included:

- extension of the workpad to accommodate maximum future movement (maximum extension was 41 feet),
- repositioning of existing grade beams,
- extension of grade beams,
- replacement of a VSM bent with a grade beam
- rework of bent VSM piling to restore plumbness; and
- intermediate VSM support modifications.

This work was completed in 2004.

Summary of Outcomes from Earthquake

- The Trans-Alaska Pipeline performed very well based on original design criteria in this, the first real test since startup.
- The special crossing segment (reported to be the first of its kind) was successful. Conventional fault crossing burial would likely have led to severe damage up to or including a spill
- Although DrQuake was imperfect, the inspection checklists proved very valuable in establishing damaged areas.
- The imperfections in DrQuake's performance highlighted improvement opportunities later implemented
- Existing repair procedures were valuable to the final repairs.

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[43] Conversation with Jim Roddick, Alyeska Pipeline Service Company, April 20, 2009.

- The use of the ICS system was appropriate; APSC was highly practiced, especially after the November 2001 spill event at Pipeline Milepost 400, and this was beneficial in organizing response.

Evolution of Alyeska Design Criteria since Denali Fault Earthquake

The Denali Fault earthquake was, as we have noted, the first test of pipeline or facility performance against the original Design Basis definition of seismic zones. As it turns out, it was also the last such test.

In 2004, Alyeska proposed – and its regulators accepted – a major change in the TAPS Design Criteria. This change implemented the following changes:

- TAPS seismic criteria were no longer associated with specific zones (e.g., Willow Creek to Valdez), as had been the case originally.
- Richter magnitudes were no longer to be used in setting the Design Contingency Earthquake
- Instead of the Richter magnitudes, Alyeska adopted the USGS PSHA seismic hazard mapping for Alaska, augmented by a specific TAPS PSHA performed in the 1990s as shown in Figure 10 (next page).

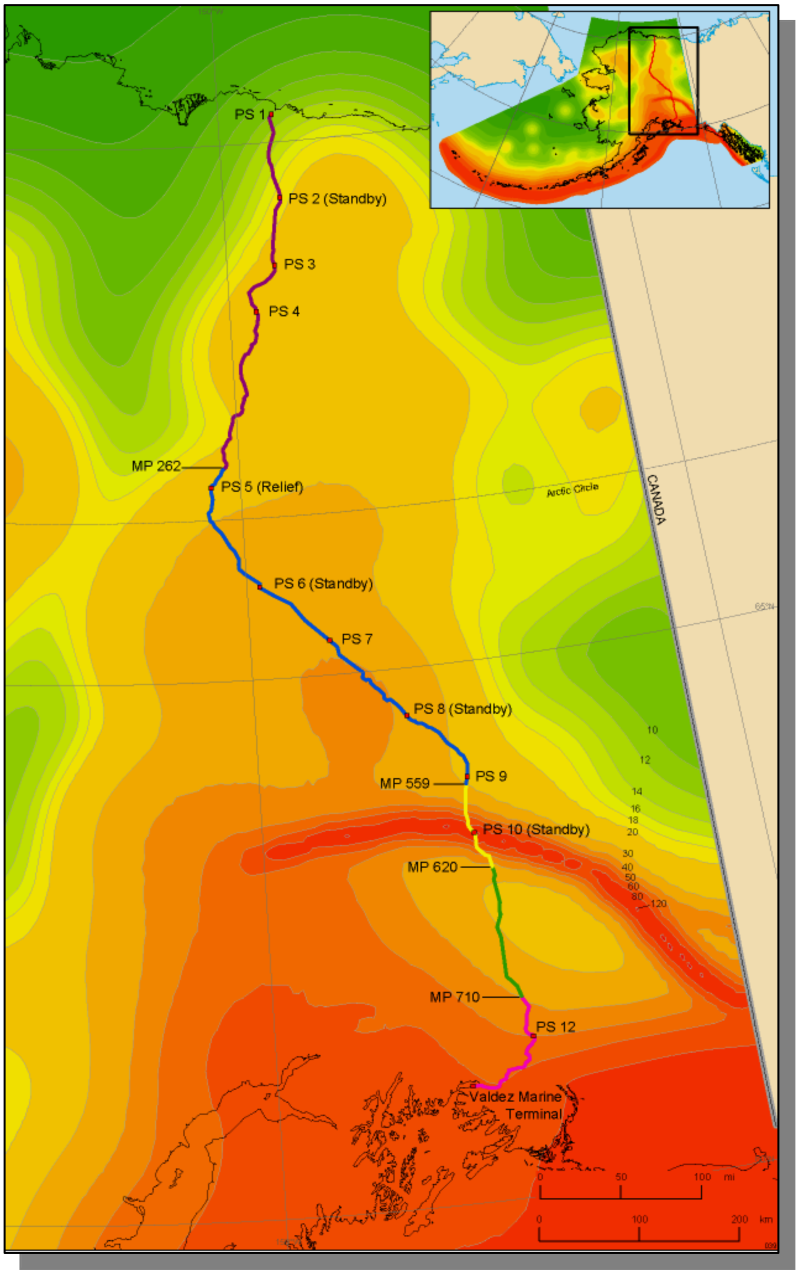

Figure 10 – Probabilistic Seismic Hazard mapping for TAPS corridor

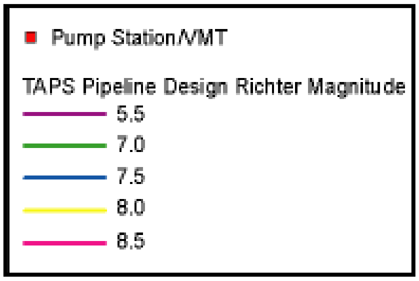

Figure 11 – Legend for Figure 10

- The "Design Contingency Earthquake" and "Design Operating Earthquake" paradigms were retired; the DCE was put aside in favor of a "Maximum Considered Earthquake" (MCE) designation consistent with ASCE 7 and NEHRP.
- This mapping shows peak ground accelerations as a function of % occurrence within a given time period; this criterion effectively sets a recurrence interval.
- The new design criteria adopt the approach of ASCE 7 and the International Building Code (IBC).

This change was proposed in a documented entitled "Modernization of TAPS Seismic Design Criteria," and authored by a team that included William Hall, who had been Newmark's protégé and collaborator in the TAPS response spectra formulation in the early 1970s.[44] As part of the justification for the change, the authors noted that the basis of the design – the use of "effective" zero period accelerations, amplified per implementation instructions and based on the TAPS response spectra – were now replaceable by spectral accelerations obtained directly from the hazard assessment mapping. This "more accurately [addressed] variation in [earthquake] intensity based on source type." However, the spectral acceleration concept was, in many ways, an advanced implementation of the work that Newmark proposed for TAPS and elsewhere in the early 1970s.

The TAPS criteria proved compatible with IBC in numerous respects. In addition, it had rational advantages in that it did away with gross zonation and accounted for geographical variation of seismicity away from primary source locations. While more conservative for the highest seismic use groups (using a 2500 year MCE as opposed to a 500 year DCE), the new approach did allow relaxation of the strength requirements for lower use structures, since design levels of base shear were scaled by ductility (enabling designers to take advantage of the ductility or yield strength).

The major advantage, however, was administrative. Because TAPS design procedures were uniquely developed, they always required special administrative procedures, one of which was special design procedures. The uniqueness caused a training burden on Alyeska and increased costs, and led to many contentious debates about the value and role of the seismic

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[44] D.J. Nyman, W.J. Hall and M.D. Anderson: "Modernization of TAPS Design Criteria for Use with IBC-2000/2003 Building Code," August 27, 2004.

program, with structural engineers often being the strongest critics. By adopting the IBC based design approach, Alyeska simultaneously accomplished several things. First, it placed the seismic design in step with prevailing methods of assessing design loading, so that no special training beyond courses available commercially or academically on the subject would be required. Second, it took advantage of the most current approach and probabilistic mapping. Third, it actually became more conservative in the earthquake return interval. Finally, it offset some of that additional conservatism by allowing earthquake response to mobilize structural ductility.

This was promulgated in 2004 with a signed memorandum by BLM, and a formal amendment by the Alaska Department of Natural Resources. With that the Stipulations – which never identified the original Newmark approach as the sole method – formally recognized the IBC approach.

Modernization of Alyeska's Earthquake Monitoring System

The past decade in Alyeska has been dominated by a large scale initiative called Strategic Reconfiguration (often abbreviated SR). This initiative sought to install more modern, cost effective and appropriate equipment enabling improved automation and remote monitoring of operations while reducing manning in the field.

Driven largely by SR, Alyeska has now completed a long-standing goal to turn over maintenance and monitoring of its earthquake monitoring system (EMS) to the University of Alaska Fairbanks' Geophysical Institute.

The Alyeska EMS had formerly consisted of 10 digital strong motion accelerometer (DSMA) units from Pump Station 1 in Prudhoe Bay to Pump Station 12. Every pump station except Pump Stations 2 and 3 had these devices mounted on their grounds. Most were on soil foundations, but at least one (at Pump Station 4) was mounted on a rock outcrop. The devices were linked to the alarm system at OCC via the Alyeska SCADA network.

As is the case with such devices generally, they were subject to nuisance alarms caused, for instance, by heavy equipment operation (e.g., snowplowing equipment) working on pads. Although APSC operators were able to discriminate between noise and strong motion seismic events, the monitoring and interpretation of these signals was outside the core competencies of the company. Some operations personnel voiced resentment over the seismic monitoring and "housekeeping"[45] programs, further telegraphing the low priority associated with the EMS.

The transfer of maintenance and operations to UAF has proven beneficial in several respects:

1. The DSMA devices have been upgraded and modernized.
2. The entire network of sensors operated by UAF is now used to localize earthquake epicenters and to produce "shake maps" estimating the acceleration intensities of a given event. This is more accurate than the prior system which had only a linear array from Pump Stations 1 to 12.
3. The improved shake map output now is used to generate the DrQuake output, which shows post earthquake assessment priorities.
4. Finally, the format for the DrQuake output has improved. The output is now a Web based interface built from an Access database. This web site and database is designed and maintained by DJ Nyman Associates from output supplied by UAF, under contract with APSC. It shows discipline specific and geographical specific outputs in a user-friendly format.

It must be noted that these improvements were not driven by the Denali Fault earthquake. In fact, the idea of turning over maintenance of the EMS to UAF had been in development for several years prior to the event, and was, as noted, based mostly on economic synergies. Nonetheless, the Denali Fault event highlighted the advantages of that turnover, and experience from the event and its aftermath was crucial to informing the design attributes of the new system interface.

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[45] Seismic housekeeping is a term used to encompass bracing and other means (such as straps) to secure objects (e.g., books) that could cause damage to pipeline operations or control in a seismic event. For example, objects close to control panel wiring were secured.

Closure

This paper has reviewed the performance of the Trans-Alaska Pipeline during the 2002 Denali Fault earthquake relative to:

- Original TAPS design criteria;
- Original design elements;
- The Earthquake Monitoring System, its alarm and response attributes;and
- The required engineering and repair effort.

We found that the overall system performed exceptionally well. Notwithstanding the fact that some parts of the system and/or response were imperfect, the overall design proved robust, as did Alyeska's response.

The major imperfect elements could be summarized as follows:

- Because of uncertainties inherent in original mapping, the fault proved to be almost at the extreme southerly end of the fault crossing segment, leading to some exacerbated damage in the conventional above-ground section just south.
- Because of the limited number and the linear arrangement of DSMA units visible to the Earthquake Monitoring System, there were some biasing errors that skewed the predicted maximum intensity segments south of where they actually occurred.
- The fact that a full earthquake mobilization had never occurred previously led to confusion in implementation of response.
- The shutdown was arguably delayed longer than it should have been.

Most of these imperfections have been addressed since the earthquake as follows:

- Post-earthquake reanalysis led to a very accurate mapping of the fault, and reanalysis of the pipeline during the repair process led the conclusion that restoration of original design would be more than adequate, given the very low likelihood of recurrence within the remaining life of the pipeline.
- The integration of APSC DSMAs into the UAF system has vastly improved the system accuracy.

- Along with that integration, there have been major improvements in the DrQuake processing of repair protocols, in a manner that appears to expedite required inspection and repair activities.
- The delayed shutdown of the system is the only item on this list that does not appear to have been addressed.

By way of recommendation, the author of this report believes that the new EMS reporting system should be subjected to rigorous drills to assure that responders will be guided efficiently and effectively in a real event. In addition, the shutdown protocol of the pipeline should be clarified so that prolonged continued operation does not occur.