The Trans-Alaska Pipeline System: A Systems Engineering Case Study

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Abstract The Trans-Alaska Pipeline System (TAPS) was constructed between 1974 and 1977 in response to the 1973 oil crisis. It conveys oil from Prudhoe Bay in northern Alaska to the port of Valdez in the southeast, a distance of over 800 miles (1,300 km). Building the pipeline system meant dealing with a multiplicity of complex design and management decisions that involved engineering, environmental, political, legal, security, financial, and other issues. A decision was made to run most of the pipeline above ground, supported by permafrost, which engendered an innovative and creative set of solutions. An interesting major concern was to find a way not to interfere with the annual caribou migration. Security was (and is) a big issue. Some unanticipated risks also arose, some with unintended consequences. This paper examines the responses to myriad challenges, examining it from a systems engineering and systems thinking viewpoint. Questions for discussion are suggested so that this can be used as a case study in a course on systems engineering or systems thinking.

1 Introduction

The United States geological survey has estimated that areas north of the arctic circle have up to 90 billion barrels of oil available in 25 areas (including offshore), but finding practical means of production and transportation of crude oil in these harsh conditions present difficult challenges. (A barrel, abbreviated bbl, contains 42 U.S. gallons, or 159 L.)

In June of 1968, a joint venture of ARCO and the Humble Oil and Refining Company announced the discovery of *recoverable reserves*—oil that is technically and financially feasible to extract—of 5–10 billion barrels in Prudhoe Bay in

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northern Alaska. The climate there is severe: the average daily mean temperature is –21 °F (–29 °C) in February (the coldest month) and 47 °F (8 °C) in July (the warmest).

This area of Alaska, known as The North Slope, has a tundra climate. Prudhoe Bay is home to thousands of migratory birds, caribou, and other wildlife. It is also the largest oil field in the United States. The Trans-Alaska Pipeline System connects this field with a year-round navigable marine terminal in the south of Alaska via a 48″ (122 cm) diameter pipe, which runs through over 800 miles (1,300 km) of Alaskan wilderness. About half of the pipeline is above ground, pictured below.

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The pipeline's statistics are staggering: It can hold over 9 million barrels of oil and is currently pumping approximately 200 million bbl/day. Historic throughputs have exceeded 750 million bbl/day! Since its inception, it has pumped more than 17 *billion* barrels of crude oil and has supported over 100,000 jobs in Alaska.

The motivation for building the pipeline has primarily political roots: During October 1973, there was a war between a coalition of Arab gulf states and Israel, which began with an Arab sneak attack on Israeli positions. Israel had anticipated and was well-prepared for such an eventuality, so the war lasted less than 3 weeks; however, there were far-ranging implications to the cost of the world's oil.

In an initial protest to the United States' support of Israel in this war, the Arab members of the Organization of Petroleum Exporting Countries (OPEC) reduced their oil production rate by 5 % almost immediately. Then, when President Nixon ordered additional military support to Israel, Saudi Arabia led OPEC to declare a complete embargo of oil going to the United States, Canada, Japan, the Netherlands, and the United Kingdom. The primary result of the embargo to worldwide oil prices was swift and dramatic, leading to a quadrupling of the price of oil and directly inspiring the interest in building the pipeline. The engineering, environmental, and other challenges that arose were daunting.

The estimated cost of the pipeline when it was first proposed in 1969 was $900 million. Within a year, that estimate had risen by 122 % to $2 billion. By 1973, that estimate rose again to a range of $3–4 billion and then to $7.7 billion by 1976. The final cost was estimated to be $8 billion. Construction of the Valdez Marine Terminal cost an additional $1.4 billion.

2 Challenges

This was a very complex project involving many challenges, which make an ideal case study for systems engineering and systems thinking. Costs were consistently underestimated. Challenges from native people and conservationists—the final Environmental Impact Statement of 1972 ran to 6,500 pages in 9 volumes—were numerous and strong. The engineering challenges of supporting the pipeline above ground on permafrost were unprecedented.

In the end, all arguments against the pipeline were ultimately rejected and the pipeline was built. Following is a more complete description of some of the more significant challenges.

2.1 Technical

From a systems engineering perspective, there were many architectural and design alternatives which needed to be analyzed to assess the very difficult technical challenges of transporting oil from Prudhoe Bay to Valdez. Oil emerges from the ground at temperatures as high as 160 °F (71 °C). Even though it cools a bit over its 800-mile journey, fluid friction tends to keep the temperature up. Oil pipelines in less severe environments have no problem in sending the oil at elevated temperatures, but the most significant problem for this Alaskan oil is that the subsoil on the route consists mainly of *permafrost*, which is defined as rock or soil material that has remained below 32 °F (0 °C) continuously for two or more years.

Running the pipe along permafrost, be it buried or above ground, presents difficult engineering challenges, because there is no solid ground on which to support it and the pipes are hot. In more temperate climates, buried pipe would not soften or melt the surrounding ground. Above-ground support structures would normally rest on existing rock or concrete pads, but no such thing is possible in Alaska because of the permafrost. The supporting structure could rest on permafrost; however, it must not be allowed to get warm, lest it melt the permafrost. The solution that was devised was to have vertical support members (VSM) made of 18″ steel pipe placed every 50–70 feet along the pipeline. Each pair of pipes had a cross member (pictured to the right) with a Teflon base that allows lateral movement in the case of expansion and contraction and seismic activity.

“Thermal” VSMs are used on most of the above-ground sections. These have pairs of 2″ pipes running from the base below ground to aluminum heat radiators at the top. The pipes contain anhydrous ammonia refrigerant which carries heat away from the permafrost and recycles itself without requiring any sort of control system.

All types of oil lines need to be cleaned constantly and checked for corrosion. This is accomplished in several ways. First, at the head end, prior to oil entering the main pipeline, water and gas is removed from the oil. Second, corrosion-inhibiting chemicals are added to the oil before it goes into the main pipeline. In the main pipeline itself, devices known as “pigs,” shown to the right, are inserted into the pipeline and are pushed through it by the flow of oil Some pigs just scrape and clean the walls of the pipe. Other pigs—so-called “smart pigs”—can test things like the extent of corrosion and the thickness of the pipe wall.

2.2 *Political*

Political and environmental concerns began campaigns that successfully halted pipeline construction from 1970 to 1973.

Recall that Alaska was purchased by the United States from Russia in 1867 for $7.2 M, in a deal brokered by Secretary of State William Seward, which was at the time ridiculed as “Seward’s Folly.” In 1902, prior to statehood, the U.S. Department of Agriculture set aside 16 million acres (64,750 km^2) as the Tongass National Forest. An Alaskan native group, the Tlingits, believed that the land belonged to them and attempted to sue for its return. In 1959, Alaska became the 49th state under President Dwight Eisenhower.

A cash settlement of $7 M was offered and rejected. A group called the Alaska Federation of Natives suggested that a more appropriate settlement should include $500 M and 40 million acres. Under President Richard Nixon, this group agreed to abandon its land claims in favor of a settlement of nearly $1B and 148.5 million acres (601 thousand km^2).

3 Alternatives Considered

As now built and functioning, the pipeline consists of 800.3 miles (1,288 km) of stainless steel pipe, 48″ (122 cm) in diameter. 420 miles (676 km) of the pipe are elevated on 78,000 supports that descend into the permafrost and have a unique system to support the pipe above ground while the supports are resting on permafrost.

Befitting of a systems engineering approach, before a solution was chosen, multiple alternatives were suggested and considered, as listed below.

3.1 The Boeing RC-1

The Boeing Corporation proposed the development of a mammoth transport aircraft. It was to have a wingspan of almost 478′ (146 m). In contrast, the largest cargo aircraft in service today is the Antonov An-124, with a wingspan of about half that. The RC-1, as it was called, was to be powered by 12 Pratt and Whitney JT9D jet engines. The RC-1 would have been about twice the size and weight of the An-124, but would have carried about five times the payload.

A unique part of the design was the runway system that was conceptualized, which consisted of three parallel, simultaneously utilized runways. The outside runways were used for landing only and the center strip was used as a taxiway. Aircraft unloaded at the end of the runway. The lightened plane could easily take off on the downwind.

3.2 Submarines

Another fascinating design was proposed by the General Dynamics company and consisted of a proposed fleet of submarines that would navigate under the polar ice caps. There would be a total of 17 boats, each costing $700 M for the conventionally powered modes. Shore facilities would add another $2–3B.

Nuclear-powered versions were also considered. They would cost an additional $25 M each, but because the nuclear subs are faster, only 14 boats would be needed.

It was suggested that that using submarines would have provided a significant additional political advantage, too, in that the subs could travel undetected to a variety of ports, depending on any current geopolitical situation. In the end though, the fuel consumed and other maintenance and operational expenses made this solution impractical.

3.3 Extension of the Alaska Railroad

The Alaska Railroad has its southernmost terminus at Seward—about 125 miles (201 km) south of Anchorage, and going northward from there connects the state's main population centers of Anchorage and Fairbanks, where it terminates, a distance of approximately 470 miles (756 km). In order to serve the pipeline, track would have had to be built on the northern end from Fairbanks to Deadhorse (at Prudhoe Bay) and on the southern end from Seward to the oil tanker terminal at Valdez on Prince William Sound. Despite being the snowiest city in the United States, Valdez has a long history as a commercial fishing port, navigable year-round.

3.4 Ice-Breaking Tankers

In 1969, Humble sent a specially modified oil tanker, the *Manhattan*, to test the theory that ice-breaking tankers could be used to transport the oil through the Northwest Passage from the Atlantic Ocean to the Beaufort Sea. Although the westward journey was completed, multiple cargo compartments flooded, and the course had to be changed during mid-journey due to extreme weather conditions. Canadian Coast Guard ice-breaking cutters escorted the Manhattan on its return trip.

The *Manhattan* was able to make a second successful trip in the summer of 1970, but the experiment was, nevertheless, viewed as a failure. There was simply too much risk of human casualties and oil spills.

4 Risks and Unanticipated Consequences

4.1 Security Risks

Obviously, the security of the pipeline is a clear and increasing concern. The *Anchorage Daily News* reported in 2006 that an organization affiliated with Al

Qaeda put postings on their web site that encouraged attacking the pipeline with bullets or explosives.

In one of the better-known incidents, an Alaska resident shot one hole into the pipeline in 2001. This attack took place on a section that had particularly high pressure, and the result was a plume of oil that rose 75 feet into the air! Almost 300,000 gallons of oil was spilled before the system was shut off. A crew efficiently repaired the break and restored normal flow within three days. The cleanup of the tundra, of course, took much longer. The photograph to the right is a patch to a hole in the pipeline caused by a bullet.

The current security system consists of fences, armed guards, and access controls at the pump stations and other vulnerable facilities; periodic aerial and ground patrols of the pipeline; intrusion detection systems at some facilities; and an emergency communications system. Alyeska, the pipeline operator, has plans in place to expeditiously involve federal and state law enforcement agencies for assistance if necessary. Security and oil spill assessment exercises have been conducted with satisfactory results.

In the event of deliberate attack or unintentional leaks, there are three redundant leak detection systems:

- A system which compares the amount of oil entering the pipeline with that exiting it
- A system which compares calculated flow with reported flow
- A system of flow and pressure sensors than can detect and localize anomalies

4.2 Unanticipated Consequences

One of the biggest concerns from the public was interference with caribou migration. There are two large caribou herds, each now numbering in the tens of thousands, in the Alaska National Wildlife reserved, the "Porcupine" and the

Central Arctic. Each year, in early March, the herds gradually migrate northwards towards the oil fields. Not impeding their migration is one of the reasons for the above-ground pipeline. Opponents feared that the pipeline would negatively impact their migration and threaten their very existence. Surprisingly, the herds have flourished! In 1977, the Central Arctic heard was estimated to be about 6,000—it is now estimated to be over 27,000. It is suspected that the heat generated by the pipeline makes a better environment for calf-bearing.

On the human side, there were some significant negative unanticipated consequences in Fairbanks, which became the center for hiring pipeline construction staff and to warehouse equipment. The pipeline developers were paying top dollar for construction staff, well over twice the existing salaries. This was a strong incentive for hordes of prospective employees to flock to Fairbanks. The population of Fairbanks doubled between 1970 and 1975 and continued to grow thereafter. But the additional population and the wage disparity led to disproportionate increases in the cost of clothing, food, and housing and to a large increase in all types of crime, including violent.

Native Americans were also adversely impacted. The pipeline development company was required by law to hire at least 3,000 Native Americans. After the pipeline's construction, many of these employees returned to their villages, after having received a sometimes ten-fold increase in their salaries. This change in lifestyle and cultural integration was difficult for many to resolve and led them to abuse alcohol and drugs and to abandon their native culture. Many subsequently left their native villages, which suffered deeply from the decreased population.

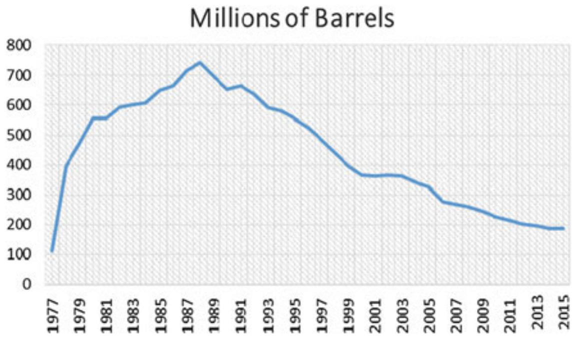
5 Conclusions

Despite the difficulties and dire projections, the pipeline has been enormously successful.

Consider that:

- Concerns about preventing migration seemed to be wrong. In fact, the Central Arctic herd which numbered about 6,000 in 1977 grew to over 27,000 by 2006. The long-term impacts are unknown.
- Fears about the effect of earthquakes were alleviated when a 7.9-magnitude quake struck on the Denali fault, described as one of the largest earthquakes in American history. Although there was some minor damage to the pipeline, it did not rupture.
- Although there have been a number of pipeline spills over the years, none have been devastating. (The Exxon Valdez spill is not considered to be pipeline-related.)

- Oil production has been as robust as anticipated. The chart below shows the annual throughput from 1977 to 2015.



6 Questions for Discussion

Question 1: Advances in systems engineering are often the result of either technology "push" or competitive advances in technology. At other times, they are clear outgrowths of non-technical factors, such as political, economic, or environmental ones, such as the development of electric automobiles. Can you suggest some other examples of advances in system design or systems engineering whose development was inspired by non-technical factors?

Question 2: Perform a "back of the envelope" trade study of the four proposed alternatives, any other obvious alternatives you can think of, plus the solution chosen. What would have been the most important criteria? How would they be prioritized? What information about each alternative would be required?

Question 3: The motivation for building the Trans-Alaska pipeline and the responses to the various challenges—political, environmental, and technical—were numerous. What do you think would have happened if there hadn't been a war, if the conservationists hadn't raised concerns about caribou migration and other effects? Would the pipeline have been built at all? Would the technical challenges have been as great? Can you think of other scenarios and solutions?

Question 4: The Keystone pipeline consists of several operational stages and a proposed expansion segment, Keystone XL. The existing segments total 2,151 miles (3,461 km) and carry Canadian crude oil the U.S. Midwest and Oklahoma. All of it is buried at least 4′ (122 cm). If constructed, it would consist of several additional segments. If the XL project is ever completed, it would carry American crude oil from Baker, Montana to Cushing, Oklahoma. This is a highly-charged political situation. President Obama is against Keystone XL, largely because of fears of effecting climate change. What lessons, if any, from the Trans-Alaska Pipeline System can be applied to Keystone XL?

Question 5: The security of the pipeline currently depends upon planning for incidents, periodic inspections, dedicated communications, and traditional "guns, gates, and guards." In light of the changing threat situation, what vulnerabilities may now be exposed and what countermeasures could be put in place to protect the oil and the environment from attack?

Question 6: As can be anticipated in projects of this magnitude and diversity, many unanticipated consequences have arisen. A few are discussed in this paper. Can you envision any other potentially unanticipated consequences? Can you think of any mitigations for the risks or exploitations of the positive ones?

Bibliography

1. Alyeska Pipeline Service Co.: Pipeline Operations: Throughput. http://www.alyeska-pipe.com/TAPS/PipelineOperations/Throughput. Accessed 23 April 2016
2. An Analysis of the Economic and Security Aspects of the Trans-Alakka Pipeline: U.S. Department of the Interior, Assistant Secretary—Program Policy, Office of Economic Analysis, Washington DC, December 1971
3. Anderson, R.W.: Alaska Pipeline Doomsayings [sic] Revisited, 1/17/2006. http://www.mrc.org/news/alaska-pipeline-doomsayings-revisited. Accessed 27 April 2016
4. Arctic Power ANWR Information Brief: Do the Caribou Really Care? http://www.anwr.org/features/pdfs/caribou-facts.pdf. Accessed 22 April 2016)
5. Banet, A.C.: Oil and Gas Development on Alaska's North Slope: Past Results and Future Prospects. Bureau of Land Management (1991)
6. Canfield, M.: Statement before the U.S. Senate Committee on Energy and Natural Resources, September 26, 1977
7. Chance, N.: The Arctic National Wildlife Refuge: A Special Report. http://arcticcircle.uconn.edu/ANWR. Accessed 15 April 2016
8. Coates, A.P.: The Trans-Alaskan Pipeline Controversy: Technology, Conservation, and the Frontier. University of Alaska Press, Fairbanks (1993)
9. Jacobs, D.: The caribou question, vol. 19, No. 2. Property and Environment Research Center (2001)
10. Lovins, A.B., Lovins, L.H.: Brittle Power: Energy Strategy for National Security. Brick House Publishing Company (1982)
11. McKibben, B.: One guy, one rifle, and an oil pipeline. Los Angeles Times (2001)
12. Moore, S., Griffith, J.: Lessons for the keystone XL pipeline debate. The Heritage Foundation Backgrounder #2977 on Energy and Environment (2014)
13. Pipeline Facts: Alyeska Pipeline Service Company. http://www.alyeska-pipe.com/TAPS/PipelineFacts. Accessed 19 April 2016
14. Reichart, D.: Positive and Negative Externalities. https://mba651fall2007.wikispaces.com/Positive+and+Negative+externalities. Accessed 21 April 2016
15. Robert Douglas Mead: Journeys Down the Line. Doubleday & Co., New York (1978)
16. Roscow, P.J.: 800 Miles to Valdez: The Building of the Alaska Pipeline. Prentice-Hall, Englewood Cliffs (1977)
17. Strohmeyer, J.: Extreme Conditions: Big Oil and the Transformation of Alaska. Todd Communications (1997)
18. The ice above, the giant below. Popular Science, p. 182 (1982)

19. United States General Accounting Office: Report GEO/RCED-92-58BR, Trans-Alaska Pipeline: Insuring the Pipeline's Security (1991)
20. Vogely, W.A.: An Analysis of the Economic and Security Aspects of the Trans-Alaska Pipeline. U.S. Department of the Interior, Office of Economic Analysis (1971)
21. Wikipedia Contributors: 1973 oil crisis. Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=1973_oil_crisis&oldid=714746302. Accessed 19 April 2016
22. Wikipedia Contributors: Boeing RC-1. Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Boeing_RC-1&oldid=665633524. Accessed 19 April 2016
23. Wikipedia Contributors: Keystone pipeline. Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Keystone_Pipeline&oldid=714186652. Accessed 25 April 2016
24. Wikipedia Contributors: Oil reserves. Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Oil_reserves&oldid=713347191. Accessed 19 April 2016
25. Wikipedia Contributors: Prudhoe bay oil spill. Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Prudhoe_Bay_oil_spill&oldid=691263249. Accessed 19 April 2016
26. Wikipedia Contributors: Trans-Alaska pipeline system. Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Trans-Alaska_Pipeline_System&oldid=710757698. Accessed 19 April 2016
27. Wikipedia Contributors: Yom Kippur war. Wikipedia, The Free Encyclopedia. https://en.wikipedia.org/w/index.php?title=Yom_Kippur_War&oldid=715794890. Accessed 19 April 2016

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