MINIMIZING FAILURES TO PVC WATER MAINS

Roy Brander, P.Eng.
Sr. Infrastructure Engineer, Waterworks, City of Calgary

ABSTRACT
The city of Calgary, Canada, is notable both for the depth of its commitment to PVC as a material for water & sewer mains, and the low failure rate it has experienced them. The break rate in the early 1990s, ~0.2 failures/year/100km, was roughly one-quarter of the average for 10 other Canadian cities[1], and less than 1% of the break rate for poly-wrapped ductile iron pipe in the same environment. The paper offers a hypothesis that this success stems from a tradition of extraordinarily careful and conservative installation methods and specifications that evolved in Calgary during a period when well-protected metallic pipe was installed with great care, just before PVC became an AWWA-specified material type. Some details of these specifications and the rigorous inspection procedures that enforce them are offered.

INTRODUCTION

Calgary is a city with a population of one million, in the foothills of the Rocky Mountains of western Canada. It has reached that population in a remarkably short time through rapid growth, rising from a population of just over 100,000 in 1946 to grow ten-fold in 58 years, a growth rate of four to five percent per year. Its population density is typical of western North America, with an average of nearly five metres of water mains constructed for every added person. (Also five of sanitary sewer, four of storm sewer, and like amounts of other utilities.)

Currently, 20 000 or more new citizens each year require the construction of 100 to 120 km of new water mains. The cost of this construction is increased by the necessity in Calgary's climate to install water and sewer mains nearly 3 metres deep in the soil. Replacement costs are much higher than original installation, some 450 Euros/m of water main.

Calgary allowed PVC materials in 1978. The effectively all-PVC installation new main for 25 years, plus some 525km of metallic main replaced with PVC since 1981, has given Calgary an inventory of almost 2 000km of C900 PVC, almost exactly half of its water distribution main (that under 500mm diameter).

A similar length of metallic distribution mains sustains over four hundred repairs per year (1.9M Euro), held down to that break rate by 12 km of replacement (4.8M Euro) and 1.8M Euro of cathodic protection programs. This (capital + operating) budget is over 300 times higher than the infrastructure management budget for a similar amount of PVC.

It needs to be noted, however, that PVC failures can be more costly and damaging than a typical metallic main failure. Some PVC breaks in Calgary have been cracks that propagated for a full pipe length, resulting in massive water loss and even property damage. Ensuring this break rate is absolutely minimized remains a high priority for the utility.

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[1] Rajani, Balvant, and McDonald, Shelley, *Water Mains Break Data on Different Pipe Materials for 1992 and 1993*", National Research Council of Canada, 1994. (Rates of 0.7 to 0.9 were reported.)

CORROSION RATE OF PVC WATER MAIN

Corrosion is defined as the degradation of any material by its environment. Metallic corrosion – rust – is the best known, but non-metallic materials such as concrete and wood also change and fail with time. Environments with abrasion or sunlight corrode plastic.

Water main is subjected to neither, unless "pigging" a main to clean it – so far never required in Calgary – causes some abrasion decades in the future. Neither Calgary, nor Edmonton, the other large city in Alberta with a long history with PVC, has ever been able to detect a difference between newly-installed PVC main and samples removed after a quarter-century in the ground.[2] If it has a corrosion rate, our material is too young to detect it.

CAUSE OF FAILURE OF PVC WATER MAIN

Figure 1, below, shows that the 20 breaks that Calgary has recorded on its inventory of PVC

Repairs to PVC Mains, Calgary, 1991-2004

Loc'n	Year	Pipe Age	Type	Comments	km PVC*	Brks/ 100km	New Unit
service tap	1991	6	fitting leak	cu service leaking	629	0.159	
service tap	1992	2	cracks	pipe destroyed at service	724	0.138	
pvc main	1993	9	fitting leak	coupling & robar			
pvc joint	1993	7	joint leak	split bell on main	813	0.246	
service tap	1994	12	cracks	hole in pipe split both ways	905	0.111	
pvc joint	1995	2	longit. split	split at bell			
pvc joint	1995	4	angle split	cracked tee			
service tap	1995	6	longit. split	pvc split ran from cu service			
pdi/pvc	1995	8	leak	improper PDI-to-PVC pipe clamp	997	0.401	
service tap	1996	2	fitting leak	no comments			
pvc main	1996	5	longit. split	pvc break	1081	0.185	
pvc/valve	1997	5	fitting leak	pvc break			
pvc joint	1997	16	longit. split	split bell, chunk of pipe blown out	1186	0.169	
pvc main	1998	4	longit. split	pvc main split	1309	0.076	
service tap	1999	4	longit. split	main split at main cock			
service	1999	4	fitting leak	cu pulled out from main cock			
pvc main	1999	7	fitting leak	broken saddle, hole worn in pvc	1419	0.211	
--	2000	--	–	no failures in 2000	1511	0.000	17
--	2001	--	–	no failures in 2001	1603	0.000	15
pvc joint	2002	11	joint leak	deflection at joint	1711	0.058	15
pvc joint	2003	12	joint leak	rolled gasket at joint of 400mm	1830	0.055	13
pvc joint	2004	17	joint leak	over-inserted spigot 400mm	1950*		

* PVC Inventory given as a mid-year average; Calgary's system has been growing so fast that a reduction in breaks/km can be obtained by merely giving the end-of-year inventory length.
2004 value is estimated, and 2004 is not given a break-rate as more may occur.

main between 1991 and early 2004. The break rate is so low that the usual unit of breaks/100km/year has become unwieldy, needing decimal places when engineers prefer small integers. With metallic main breaks, a five-year moving average suffices to smooth out yearly weather-caused variation to a steady picture. With PVC breaks, so fewer in number that the break-rate can quadruple or go to zero in a given year, a ten-year moving average

[2] Doug Seargeant, Infrastructure Engineer, Epcor Water, Edmonton Canada, personal communication, 2001. Epcor engineers deliberately removed some PVC main installed in 1976 and were unable to find any mechanical or chemical changes to the material from the time of installation.

was needed. The rightmost column of figure 1 proposes, therefore, a new unit for comparing PVC failures: ***repairs/1000km/decade****,* using a ten-year moving average.

It is the cause of all these breaks that is significant. None have been deemed by Calgary's five corrosion technicians, who perform all failure analysis, to result from corrosion in the classic sense. The rows with "service tap" in the left column came from cracks that propagated away from a tapping point or a saddle clamp. The other causes: over-inserted spigots that started a split at the next bell; a pipe deflection that bent the pipe or again started a crack at a bell; leakage at a gasket; a bad insertion that "rolled" a gasket; or the placement of the pipe against a sharp rock.

As long as sharp rocks are not defined as a reasonable installation environment, all of Calgary's PVC failures result from errors of installation. *Every single one.*

It is thus essential for minimization of PVC water main failure to have the strictest possible controls on installation procedure. In this regard, Calgary has had good fortune that was well-disguised as an expensive decade of very bad fortune; our reaction to it created an institutional standard of installation specifications and inspections that is very strong.

HISTORY

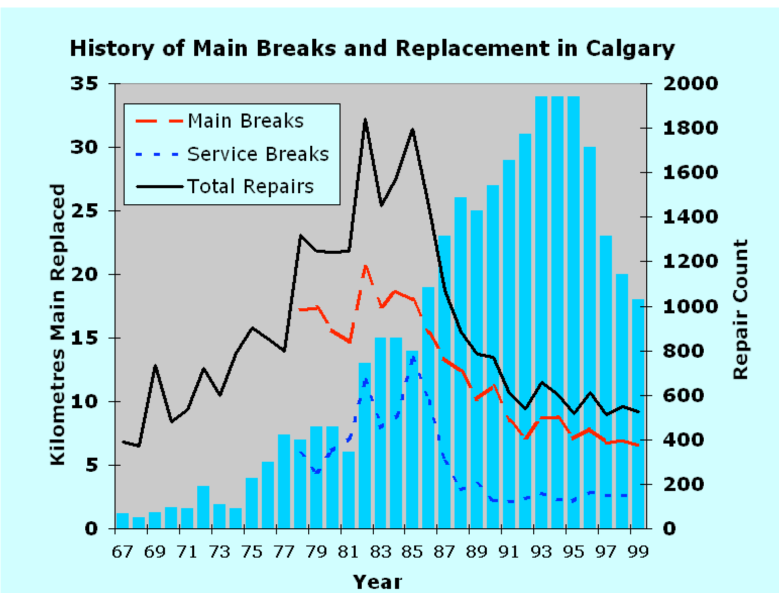
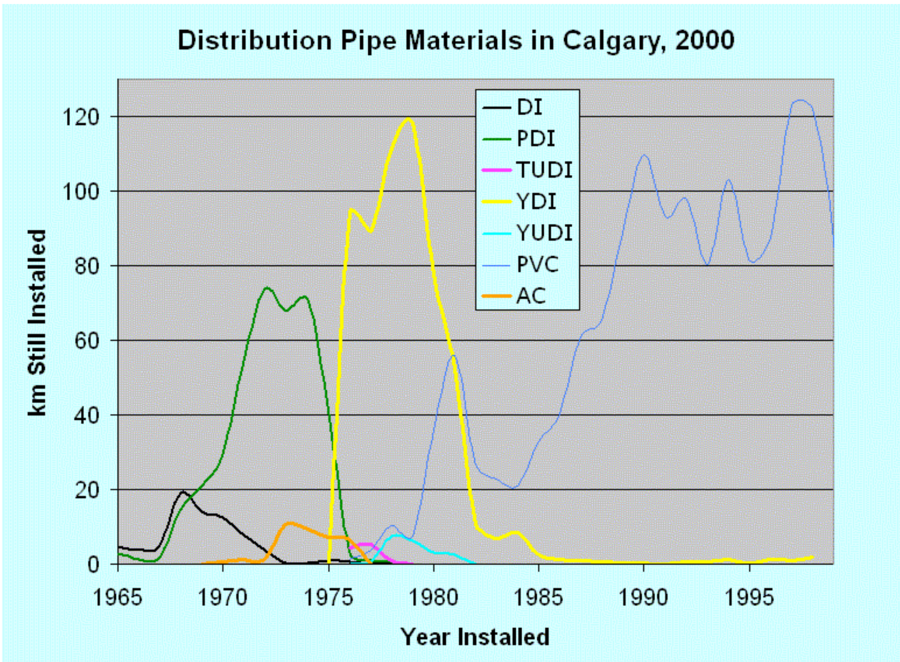


Figure 2, at left, shows the story of Calgary's difficulties with metallic water pipe and part of their response to it. Between 1971 and 1983, Calgary's repairs per year jumped over four-fold, from about 400 to 1600 and even 1800 per year. The rate shocks from the rising repair costs and customer complaints became the major issue facing the utility.

The even more expensive response was a huge and rapid increase in main replacement, as shown by the blue bar chart in Figure 2, from less than 5km/year to over 25 km/year. This increase was actually continued to 34km/year after break rates began to fall; it was not easily determined at the time that another "wave" of repair increases was not on the way as different generations of pipe materials moved through their lifecycle. It was not until the mid-1990s that a comprehensive research project was begun to determine an optimal replacement level. The project took an inventory of all mains of all material types, computed their various repair history patterns, and projected a lifecycle for each.

In the late 1990s, it began to be clear that the worst mains had largely been replaced and a new "demographic boom" of aging pipes was not immediately to be feared, and the rate of main replacement was slowly stepped down.

The trends at the end of Figure 2 have continued for these past five years: breaks continue to average about 400-430 per year, and main replacement has been further reduced, standing in 2004 at only 12 km/year. In partial substitute for some of the main replacement, Calgary has retrofitted 15-20km/year of DI with cathodic protection anodes since 1999, and in 2004 will retrofit ~35 km of DI and CI. Combined with 12-15 km/year of replacement, Calgary expects this to hold breaks to the current level over some decades to come.



The other aspect of Calgary's history with water mains is the crucial one to the thesis of this paper.

Figure 3, at left, shows the kilometres of main in Calgary's system in the year 2000 vs. the year the main was installed. It thus shows a graphical story of Calgary's preferred mains materials throughout the period of concern, just after cast iron was abandoned. All the material types ending in "DI" are the same ductile iron pipe; the one labeled just 'DI' is 'bare' ductile iron, the rest are various forms of coating or wraps that all purported to reduce corrosion to a negligible level. The one most used before Calgary took the lead for the industry in promoting YDI, was the DIPRA-recommended solution of "PDI", an 8-mil (0.2mm) polyethylene wrap applied in the field. Calgary did not find PDI to have a sufficiently lower break-rate than 'bare' DI at the time the break-rate was soaring, and developed a better corrosion control for DI water pipe.

Calgary in the 1970s was a predominantly oil-industry city with a vast array of oil industry service companies, many of which specialized in pipeline corrosion control. The preferred installation for metallic pipelines in that industry was "YDI", yellow-jacketed ductile iron.

The 'yellow jacket', as shown in the two photographs of Figure 4, above, is a 40mil (1.6mm) thick polyethylene coating which is extruded directly onto the pipe in the factory with a strong bonding agent to permit no gap between. The system was developed for welded oil pipelines; Calgary's innovation was to get the coating manufacturer to extrude it onto bell & spigot mains used for water. Even this coating, alone, has proven unable to control corrosion of DI in Calgary's more aggressive soils (resistivity <2000 ohm-cm).

The specification introduced in 1973 required not just a yellow-jacket coating on all DI pipe, but the level of cathodic protection used in the oil industry and recommended by NACE (National Association of Corrosion Engineers). In practice, this comes to a magnesium anode for roughly every 100m of pipe of 150mm diameter – about 16 pipe-lengths. Calgary uses 32-lb (~15kg) anodes, getting roughly 20 years of protection from them before they need to be replaced. One anode per 16 pipe-lengths necessitates electrical bonding straps to connect pipe-lengths, along with extreme care to avoid scratches in the coating, as indicated by the picture of pipe resting on old tires after 'jeeping' (electrically check the coating integrity), both shown in Figure 5, below.

To prevent scratches from occurring during installation, the pipe is moved with cloth straps, not chains; and bedded in 150mm of sand or "pea gravel" (smooth rock, 10-15mm) followed by an additional 150mm to cover the top of pipe. Only then is granular fill such as gravel or native soil backfill permitted. The electrical continuity of the pipe, and current flow from the anode, is tested before backfill is complete. Avoidance of coating scratches is crucial.

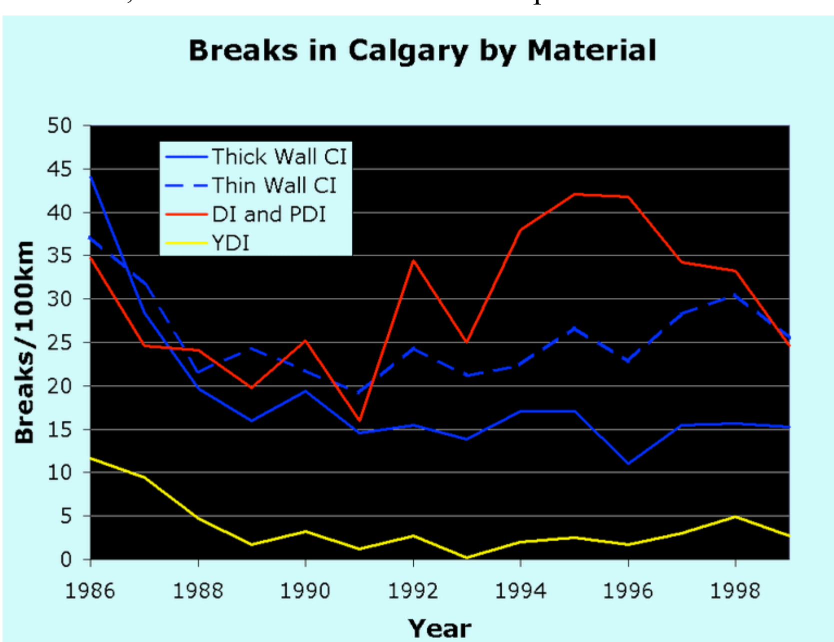


Figure 6, at left, shows the break-rate for Calgary's metallic distribution mains in recent years. DI and PDI are lumped together into one because the PDI on average has only about 30% fewer breaks than "bare" DI, in Calgary's experience. The YDI pipe, with a better coating and cathodic protection, has only 10% the break rate of PDI. The 2-5 breaks/100km/year that do occur, happen at the tiniest breaks in the coating, if the cathodic protection is lost or 'shorted out' through a copper service.

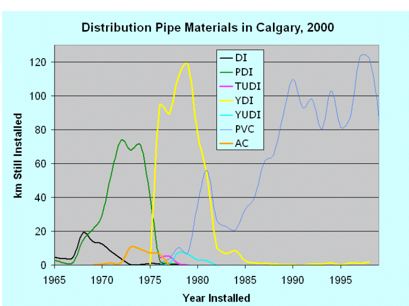
The relevance of this to our current successes with PVC stems from the change in mindset that was required of both City of Calgary main replacement staff and from all contractors when installing water mains in new subdivision developments inspected by City staff.

That success of YDI rested on painstakingly correct installation, and the 1970's saw a massive change in standards and 'mindset' of developers, contractors, and City construction crews. YDI construction required significantly greater expense for the construction, a requirement for development that would have been politically very difficult to ask, had not there been the public awareness of the main break problem and deep public support for an eventual end to it.

This gave the Waterworks Chief Engineer of the time, Jim Bouck, the support to enforce the new standards and require a slower and more complex construction process. The coating raised the cost of the DI main itself by half. The 'jeeping' of the coating by city corrosion technicians, the extreme care not to scratch the main, the bedding in clean sand, and the installation of anodes, all slowed down the number of metres constructed per day and added staff to the crew, raising costs even further. Estimates of construction costs are always approximate as they differ significantly from one job to another, but a safe estimate would be that the switch from PDI to YDI doubled water main construction costs.

Even with the added public costs of monitoring and repairing the cathodic protection systems and replacing exhausted anodes, the YDI main, with its 90% reduction in break-rate and (at least) doubled lifecycle has been worth it.

Construction with YDI for water main was a well-established construction practice for some three years when PVC mains were first used in quantity in Calgary in 1978. Once Mr. Bouck added PVC C900 to the allowed materials in Waterworks specifications, YDI installations suffered a precipitate decline in favour of PVC, as indicated by the yellow and blue lines on Figure 3, repeated at left (original on page 4).



Two factors contributed to an opportunity to set very high standards for the new PVC construction. Firstly, PVC, as a new material, endured outspoken and strong criticism from the DI pipe industry, particularly at that early time. City engineers and developers alike were thus concerned that the new pipes would be fragile and vulnerable to stress regression failures if nicked or scratched during installation. And second, the new standard of extreme care and slower pace with water main construction was now well-established in the construction community. They accepted construction standards that demanded granular bedding for PVC, extremely careful handling and tapping. These were no different from what they had already been painfully forced to accept for YDI. PVC pipe was half the price to purchase, and twice the speed of installation – *even with the new, harsh standards of inspection unchanged* – because the PVC pipe was so much lighter and required no cathodic protection.

CONSTRUCTION STANDARDS ENFORCEMENT

As with most major municipalities in Canada, Calgary follows a development model in which private development corporations install all local infrastructure and servicing in new subdivisions, to construction standards set by the municipality, and inspected regularly by City inspectors. After a "Construction Completion Certificate" (CCC) is provided at the end of installation, the city-owned utilities (water, sanitary & storm sewers, and electricity) allow connections of the new subdivision to their networks. The new subdivision infrastructure, however, remains the property (and repair responsibility) of the private developer for a period of two years. This period, experience has shown, manifests most problems related to construction errors, and is long enough for settlement to occur on all trenches to reveal poor backfill compaction. After two years, absent problems that reveal deficiencies, a "Final Acceptance Certificate" (FAC) is issued that formally accepts the "donated asset" to the City of Calgary, which takes over all responsibility for subsequent repair, maintenance and replacement. The FAC is necessary to profit in the developers' business model and forms a powerful inducement to compliance with City construction standards.

The efforts of the City inspection staff are crucial to the enforcement of those construction standards. The construction of the three "deep utilities" – water, sanitary and storm sewer – is inspected by a single group, the Water & Wastewater Joint Inspection staff. They are called the "deep utilities" because Calgary, along with other inland Canadian cities, has a remarkably deep frost penetration: up to 2.5m in severe winters. The water-bearing pipes must thus be buried almost 3m deep to avoid freezing, making construction of these utilities expensive. Figure 7, below, shows an ordinary residential street under construction with a "triple trench" that simultaneously installs the water, wastewater, and storm sewer mains, below.

Doing all three pipe systems in one large trench before any other construction of the subdivision realizes significant economies. For the City to do repairs after the subdivision is complete and the road is paved, a typical water main repair costs some 5000 Euros; main replacement runs about 500 Euros per metre at present. The original construction contractors, with no pavement or existing infrastructure to avoid, can construct the triple trench at, typically, over 400m per (12-hour) workday, but at a cost of over 3000 Euros per hour. So there is a considerable dynamic tension between the construction contractor, whose profit comes from achieving a higher number of metres constructed per hour, and the City Inspections staff, whose responsibility it is to see that those expensive repairs or replacement never have to be done.

Once a given set of construction standards is agreed upon and published, however, it is well-understood by both sides of the community that the judgement of the City's inspector is final. The author is unaware of any instance in recent decades of construction where such a judgement, if questioned at all, was not supported by every level of management of the municipal corporation. Although most construction inspectors have considerable experience, some are young former pipemen and technicians who must question the work of private foremen decades their senior. These judgements are made daily. It is unreasonable to expect inspectors to do this if they are not certain that they have the entire organization standing firmly behind them.

CALGARY STANDARDS FOR PVC WATER MAIN CONSTRUCTION

The author would like to be able at this point to offer some magic bullet, some basic added standard to those listed in the "Handbook of PVC Pipe Design and Construction", from the Uni-Bell PVC Pipe Association, which is the 'secret' of Calgary's low PVC break rates. Calgary does have exactly one suggestion to add to the accepted industry practices, but it is only a part, probably a small one, of the success story. Calgary does require sand, or clean gravel with all "potentially injurious" material removed from it, as the pipe bedding and for the first lift of backfill that surrounds the pipe. The "non-injurious" requirement effectively makes it impossible to use Calgary's native soils, as only gravel with all-rounded edges may qualify – crushed gravel may not be used. Most contractors elect to use sand or pea gravel for bedding and pipe zone fill.

This requirement, in combination with a strict prohibition for the use of any sharp objects near the pipe (save of course for tapping bits), avoids all scratches and virtually all damage to the pipe and gaskets during installation.

Aside from bedding and extra care of handling, the laurels for Calgary's low PVC failure rate would seem to come entirely from the rigidity of the enforcement of ordinary industry standards for PVC water pipe installation. Since the failures we do have come not from materials problems but installation practices, no other explanation is evident.

This is a "quality" issue, as opposed to a thing easily quantified. The perception mostly arises from site visits to some smaller centres near Calgary that do not have a permanent

inspections staff and their own pipeman and inspector training facility like ours. Anecdotal evidence is much repeated to the effect that contractors in these small municipalities are permitted installations that would be rejected in Calgary.

The installation in Figure 8, at left, for instance, was rejected because the contractor attempted to handle a without a 5-degree bend element. Calgary inspectors have learned the hard way that permitting deviations of even a few degrees on main over 200mm offer a slight but measurable risk of leakage at the gasket, which then begins a process of erosion-corrosion of the gasket, the bedding, and even the pipe itself. The leak only increases with time until finally a major failure can occur if the leak is not detected. Exactly that happened with Figure 9, right, a major failure of a 400mm main in 2003.

The huge amount of pipe installed in Calgary each year reveals the lowest-probability risks; 120 km is 20,000 pipe-lengths. If one joint in 100 were allowed a few degrees of bend that in turn had one chance in 100 of eventual failure, we would have two additional failures per year similar to Figure 9. Decades of such installation rates have made Calgary inspectors experienced with a zero-tolerance policy. No pipe over 200mm may have any joint deflection at all. No pipe of any diameter is allowed to be bent along the pipe-length, as this causes some stress. It may be conceded that PVC can of course take some stress; but Calgary's experience with field procedure is that when bending is allowed at all, it is difficult for inspectors to ensure it is kept to the limits that ensure zero failure.

Five degree bend elements are the most allowed without a thrust block; and contractors have

learned that inspectors view concrete as very cheap and repairs very expensive, so thrust blocks and concrete forms tend to be sized conservatively as shown in Fig 10, above.

One sharp object is not just allowed near PVC pipe, it is strictly required. As half the failures experienced with Calgary PVC water pipes stem from cracks that begin at service taps, they are all closely inspected. Field inspectors, who cannot personally observe more than about 10% of the construction at any one job site, require that all coupons resulting from taps be placed in a bucket for their inspection. They check each one, and dispose of them. Drawn from the ranks of our best pipemen, inspectors know the importance of sharp tapping bits, and slow, careful tapping procedure – and have experienced eyes that can tell the difference by looking at the coupon.

The inspector's tool for enforcement is the Field Work Order.

An example work order from 2003 contains the comments: "ground below pipe installation wet and spongy. Installation of pipe – REJECTED AS INSTALLED. Remove pipe and re-install pipe on a foundation that consists of stable material". A section below for "action taken" states: "(1): Remove saturated soil and replace with 40mm wash rock so that bedding gravel for storm force main sits on top of gravel for sanitary force main. (2) DOUBLE size of thrust blocks due to unstable ground conditions".   Some tens of thousands of Euros worth of work had to be moved and repeated, plus the expense of more gravel and concrete.

Not all Field Work Orders (FWO) are so expensive to satisfy; most only require the contractor to revise an hour or so of work – but one construction crew-hour may exceed 4000 Euros.

City of Calgary joint water & sewer inspection staff issued roughly 400 FWO in 2003, for some 120 km of triple-trench installation – about 350km of the three kinds of plastic pipes, so work was halted and fixed more than once for every kilometre of pipe installed; for every 330m of trench. A FWO is thus literally a daily experience for a trench contractor in Calgary, a regular cost of doing business.

Field Work Orders are archived indefinitely; inspectors also sign on the correctness of all the "grade sheets" (detailed drawings of the subdivision and all 3 pipe system's infrastructure, including services), and the valve and hydrant cards. Even where the inspector approves of all work done and has no negative comments, his or her daily work log books record all unusual or interesting notes about the construction. In recent years, these logs have been augmented by an ever-growing volume of digital photographs of the installation. Good documentation has often proven essential when disputes arise. It is never just one person's word against another's.

The long-term institutional "memory" of inspection documentation is essential to success - the contractor must have no hope of a problem being overlooked or forgiven. As this paper was being written, a Calgary contractor that had not finished selling all the lots for a subdivision for four years after the "CCC" had allowed water to flow, sought a "FAC" so that they would no longer be responsible for maintenance. A routine check showed that a FWO had never been closed and signed off by the inspector: a PVC hydrant lead was not installed at 2.8m below grade, only 2.6m. The City accordingly refused to accept responsibility for the entire kilometre of donated assets until the FWO was satisfied. The developer was automatically required to pay for digging down to the hydrant lead, and either remove and replace the hydrant lead 20cm deeper, or insulate it against frost penetration with an insulation approved by the author.

Discussion about the amount of insulation needed, given the small distance above the required depth, and the few metres of hydrant lead involved, raised a telling comment from one engineer. "The point is not how high the probability of freezing is, the point of the exercise is that *absolutely nobody disregards a requirement from a City inspector."* Not, at least, without dire financial consequences.

In an environment where the economic pressure to make one exception (then, of course, another, then another that goes even further) is relentless, a line must be drawn, and no exceptions go unpunished. An inspector questioned about how to maintain a friendly working relationship with people he saw every day and was constantly causing expensive delays, replied: "We have a polite and professional relationship; but there are no friends in this business." Many of his colleagues might disagree, but not to the point of having friendship ever prevent a field work order.

CONCLUSION

As ground movement and rocks in fill can be a cause of failure in PVC pipe, a requirement for clean, washed-rock granular fill in the pipe zone is believed to be a benefit to minimizing failure rates. Lower ground movement in the pipe-zone is likely a beneficial side effect of the deep bury needed in cold climates, but this benefit accrues to all Canadian cities, including those with much higher failure rates. A further reduction may come from a tendency to conservative sizing of concrete thrust blocks.

However, the majority of the extraordinary success rate that Waterworks and Wastewater in Calgary have enjoyed with the material is believed to come from a very strong, thoroughly documented, and rigidly enforced system of inspection of installation, and correction of the most minor construction errors. In particular, the few failures Calgary has seen have caused a close focus and "zero-tolerance" policy on excessive bending of pipe or deflections at joints. "Recommendations" about these in the Uni-Bell Guide are treated as unbreakable rules. Poor bedding and poor quality of tapping are also not tolerated.

This is a business process, a regime of procedures supported by engineers, but implemented by inspectors in the field. Construction standards from engineers are like laws drafted by politicians. It needs to be understood that laws do not reduce crime: police do.