

Pipe Whip Experiments Involving Impacts Between Pipes

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SUMMARY

Dynamic pipe impact tests were performed in order to determine the impact conditions for which a 2 inch Schedule 80 carbon steel target pipe would not be broken if it were impacted during a pipe whip event created by a postulated break of an adjacent larger parallel pipe. Such pipe/pipe impact scenarios are of special interest for the feeder pipes of a CANDU reactor because the large number of closely spaced parallel feeder pipes that carry coolant between large primary system pipes and individual fuel channels in the reactor core makes it impractical to consider providing feeder pipe whip restraints.

The testing which was performed involved simulating the behaviour of 3 inch and larger whipping pipes in order to study their impact with 2 inch target pipes pressurized at about 9 MPa with water at a temperature of about 290°C. In a conservative simulation of the worst pipe/pipe impact event which it has been predicted could occur for adjacent parallel feeder pipes (when a whipping pipe has a kinetic energy of about 10 kJ just before it impacts a 2 inch pipe), it was demonstrated that the target feeder pipe does not experience more than a 26% local reduction in its diameter. The target pipe impact conditions were also made sufficiently severe that a target pipe would rupture in order to estimate the safety factor associated with not having a feeder pipe rupture during the worst plausible feeder pipe whip event.

For all of our dynamic pipe impact tests, there was an empirical relationship between the final deformation of the hot and pressurized 2 inch target pipes and the kinetic energy of the body that impacted them. As the kinetic energy of the impacting body increased to about 30 kJ, the reduction in diameter of the target pipes increased up to a value of about 45%. For impact kinetic energies of up to 66 kJ, the target pipe diameter reduction did not exceed 62%. Cracking of the target pipes, which initiated at their inner circumference, was not observed until the kinetic energy of the impacting body was about 49 kJ while the target pipes did not rupture until the kinetic energy of the impacting body was about 66 kJ. Therefore, at least five times the energy that is expected to be associated with the worst plausible feeder pipe whip event is required before a 2 inch target feeder pipe could be cracked and ruptured if it were impacted by the whipping pipe motion associated with a postulated break for any adjacent parallel feeder pipe.

INTRODUCTION

A common 'rule-of-thumb' when initially assessing the potential consequences of pipe/pipe impacts is that a stationary target pipe may be broken by a larger whipping pipe but would likely not be broken by a smaller whipping pipe [1]. However, since the consequences of a specific pipe/pipe impact is a function of the exact properties for that impact event, the actual consequences of all pipe/pipe impacts cannot be accurately predicted by such a simple rule. For example, since the initial pipe/pipe gap limits the velocity that a whipping pipe can reach before impacting a target pipe, it is expected that a stationary target pipe could not be broken by a slightly larger whipping pipe if the initial spacing between the target and whipping pipes were not very large, so that the pipe/pipe impact velocity would be sufficiently small.

Although analytical estimates of the consequences for pipe/pipe impacts can now be made using published experimental results from static pipe crush tests as input data [2], there is not yet very much experimental data describing pipe deformations recorded in dynamic pipe impact tests. Therefore, Atomic Energy of Canada Ltd. and Electric Power Development Co. of Japan recently collaborated to perform dynamic pipe impact tests in order to provide a better understanding of the impact conditions for which a 2 inch Schedule 80 carbon steel target pipe would not be broken if it were impacted during a pipe whip event created by a postulated break of an adjacent larger parallel pipe. Such pipe/pipe impact events are of particular interest in a CANDU reactor because the large number of closely spaced parallel feeder pipes that carry coolant between large primary system pipes and individual fuel channels in the reactor core makes it impractical to consider providing feeder pipe whip restraints.

DESCRIPTION OF PIPE IMPACT TEST FACILITY

Figure 1 is a schematic arrangement drawing of the pipe impact test facility that was used. In this facility, a full scale whipping feeder pipe is created by a momentum transfer from a projectile that is accelerated by an air gun, rather than by having a blowdown force act on a broken pipe. Because the consequences of pipe/pipe impacts are considered to be primarily determined by the kinetic energy of the whipping pipe, rather than by the magnitude of the blowdown force acting on the whipping pipe at the instant that it impacts a target pipe, it is considered that this relatively simple experimental facility provides a good simulation of the whipping motion exhibited by a broken pipe, including the key consequences if a whipping pipe impacts a target pipe.

The motion of 3 inch and larger whipping pipes has recently been simulated, including their possible impact with 2 inch target pipes that were at typical operating conditions for a CANDU reactor. Each pipe/pipe impact test was initiated by having a 90 kg projectile accelerate downward until its relatively rigid 4 inch diameter hemispherical hardened carbon steel head hit an elbow welded onto the free end of a 2-1/2 meter long 3 or 3-1/2 inch A106 Grade B Schedule 80 carbon steel cantilevered empty pipe in order to create a whipping pipe. After the free end of this whipping pipe moved downward about 0.2 meters, the mid-point of its elbow impacted the mid-point of a 3 meter long span of a 2 inch A106 Grade B Schedule 80 carbon steel pipe that was pressurized to about 9 MPa with non-flowing water at a temperature of about 290°C. To simulate the very flexible supporting arrangement used for feeder pipes, which are 10 to 20 meter lengths of 3-1/2 inch and smaller pipes that each have no more than two relatively flexible restraints, the ends of the

target pipe spans used in all of the recent pipe impact tests were provided with only lateral (no axial or moment) restraints.

The energy source used to accelerate the projectile is a 0.14 m³ compressed air reservoir. By activating a quick opening valve, this compressed air reservoir rapidly pressurizes a barrel containing the projectile so that it is accelerated downward along a guide assembly. Projectile velocities of up to about 50 m/s were obtained by using an air reservoir pressure of up to about 13 MPa. After the projectile has impacted the free end of a cantilevered pipe, causing it to become a whipping pipe, the projectile is stopped by contacting a decelerator assembly that dissipates its remaining kinetic energy by forcing metal plates to slide between asbestos brake shoes. Therefore, the projectile was not involved in the impacts between the whipping cantilevered pipes and the target pipes.

The only non-conservatisms known to be associated with using our test facility for providing full scale simulations of pipe/pipe impacts involving adjacent feeder pipes are that the simulated whipping pipes were empty, rather than being filled with steam and water, that these whipping pipes were not continuously acted upon by a blowdown force and that only 2-1/2 meter long whipping pipes were used. None of these slight limitations of the testing are believed to significantly affect the test results.

The cantilevered whipping pipe and the simply supported target pipe were always mounted horizontally, and oriented perpendicular to each other, even though adjacent feeder pipes are actually parallel to each other. This experimental pipe configuration was selected both to simplify the construction of the test facility and to ensure that the whipping pipes would stay in contact with (and be stopped by) the target pipes, rather than cause only a superficial glancing pipe/pipe impact as could easily occur for parallel pipes. It is considered that this experimental configuration creates the most severe type of pipe/pipe impact that could occur between adjacent parallel feeder pipes, since a whipping feeder pipe would usually be expected to cause other adjacent parallel feeder pipes to actually experience only glancing impacts.

PIPE/PIPE IMPACT TEST RESULTS

Two tests were performed for each of three different projectile/pipe impact velocities (about 25, 38 and 51 m/s) in which 3 inch cantilevered pipes were accelerated to become whipping pipes that rotated about their rigidly anchored ends. In these tests, the velocity at which the elbow attached to the free end of the whipping pipes hit the target pipes was about 20, 30 and 39 m/s, which created localized target pipe diameter reductions of up to 6, 15 and 22% respectively. These deformation percentages are the ratio of the maximum reduction in the outside diameter of a target pipe to the original outside diameter of the target pipe. The elbows of the whipping pipes were only crushed a very small amount (always less than 5%). Figure 2 is a photograph that shows the configuration of the whipping and target pipes immediately after a typical pipe/pipe impact test.

Two additional pipe/pipe impact tests were performed for a projectile/pipe impact velocity of about 51 m/s using 3-1/2 inch whipping pipes, the largest feeder pipe size in CANDU reactors. In these tests, which involved the largest possible difference in pipe size for adjacent feeder pipes (the whipping pipes being almost twice as large as the 2 inch stationary target pipes), the velocity at which the whipping pipes hit the target pipes was about 36 m/s so that the simulated whipping pipes were associated with a kinetic energy of about 10 kJ at the moment they impacted a target pipe. Figure 3 is a photograph

showing the deformed shape at the impact point for one of these target pipes, whose diameters were locally reduced by up to 26%. This test condition, which involved a pipe/pipe impact velocity that was about 12% larger than the highest velocity which pipe whip analyses have predicted could occur for impacts between adjacent feeder pipes, was a conservative simulation of the worst pipe/pipe impact event that it has been predicted could occur for adjacent parallel feeder pipes. Therefore, these two tests were proof tests that if a large whipping feeder pipe impacts an adjacent small feeder pipe then this target pipe would not break and, in addition, its change in cross-sectional area would be sufficiently small that the fuel cooling provided by this pipe would not be adversely affected.

PROJECTILE/PIPE IMPACT TEST RESULTS

It was desired that much more severe pipe impact tests than the proof tests just described be performed in order to learn what impact conditions are required to rupture a target feeder pipe so that the safety factor associated with not having a feeder pipe rupture during the worst plausible feeder pipe whip event could be defined. Unfortunately, the existing pipe impact test facility could not easily be used to create projectile velocities significantly higher than about 50 m/s. Therefore, since the head of the 90 kg projectile had been fabricated to be approximately the same size and shape as the portion of the 3-1/2 inch elbows that impacted the target pipes in the pipe/pipe impact tests, it was decided to perform tests in which the projectile directly impacted the mid-point of simply supported 3 meter long spans of hot and pressurized 2 inch Schedule 30 carbon steel target pipes. In the projectile/pipe impact tests that were performed, the projectile was allowed to move about 0.3 meters with the target pipes before the projectile was stopped by its decelerator system in order to simulate a very severe case of the type of glancing impact which it is expected would occur between adjacent parallel feeder pipes if one feeder pipe ever breaks. In addition to allowing extremely severe target pipe impact conditions to be created, these projectile/pipe impact tests also allowed more data to be recorded (like time history plots of target pipe deformation and the impact force acting on these pipes) than could be obtained during the pipe/pipe impact tests.

Nine projectile/pipe impact tests involving five different projectile/pipe impact velocities (about 13, 25, 29, 33 and 38 m/s) were performed in which localized target pipe diameter reductions of up to 11, 45, 48, 55 and 62% respectively were created. All test specimens impacted by the projectile while its kinetic energy was increased up to 38 kJ, for which diameter reductions of up to 48% occurred, exhibited no cracking while the two specimens impacted by the projectile when its kinetic energy was about 49 kJ, for which the peak diameter reductions were 53% and 55%, contained cracks which originated at the inside surface of the target pipes directly below their impact point. These cracks locally propagated through about half of the pipe wall, as is illustrated in the photograph included as figure 4. The two test specimens impacted by the projectile when its kinetic energy was about 66 kJ, for which the final diameter reductions were 60% and 62%, ruptured. Figure 5 is a photograph of the impact zone of one of the ruptured target pipes.

Frame-by-frame examination of the high speed filming of the projectile/pipe impact tests allowed time plots of the initial deformation at the target pipe impact zones to be produced, as is indicated in figure 6. In all of these tests, there was a rapid local reduction in the diameter (crushing) of the impacted target pipes during the initial couple of msec. of the projectile/pipe impact, followed by additional target pipe crushing

and buckling deformation which takes place more slowly. The final target pipe diameter reduction was often approximately twice that which occurred during the first couple of msec. of the projectile/pipe impact.

Strain gauges mounted on the impact head of the projectile produced records of the projectile/pipe impact force, which was always of the form illustrated in figure 7. A large impact force spike, whose peak value for each projectile/pipe impact test is plotted in figure 8, always occurred about a msec. after the initial projectile/pipe contact. This force spike was followed by a force that is only about a quarter as large.

About a quarter of the total dynamic target pipe diameter reduction occurred before the impact force peaked with the other three-quarters of the dynamic pipe deformation occurring after the impact force had peaked. Some deformation even continued to occur after the projectile and pipe were separated. In contrast, during static pipe crush testing, deformation only occurs while the crushing force is increasing [2].

DISCUSSION

Figure 9, which is a plot of the maximum target pipe diameter reduction vs. the total kinetic energy of the impacting body for both the pipe/pipe and projectile/pipe type of impact tests, shows that duplicate tests produced very similar results. This figure also shows that there is a single empirical relationship between the deformation and total energy parameters for both type of impact tests. It indicates that as the kinetic energy of a whipping pipe is increased to about 30 kJ, the reduction in diameter for an adjacent parallel 2 inch pipe that is impacted by the whipping pipe will not exceed a value of about 45%. For impact kinetic energies of up to 66 kJ, the target pipe diameter reduction will not exceed about 62%. Cracking would not be expected to occur in 2 inch hot and pressurized target feeder pipes that are impacted by a whipping feeder pipe until the kinetic energy of that pipe reaches about 45 kJ. Rupture of 2 inch hot and pressurized target feeder pipes that are impacted by a whipping feeder pipe would not be expected to occur until the kinetic energy of that pipe reaches about 60 kJ.

As well as being a full scale representation of the consequences if a small CANDU feeder pipe is impacted by the whipping motion associated with a postulated break for a larger adjacent parallel feeder pipe, the test results being documented can also be interpreted as a scale representation for impacts involving larger carbon steel piping. By appropriately scaling the test parameters, the observed deformation for 2 inch hot and pressurized simply supported Schedule 80 carbon steel pipe spans should be representative of the deformation that would occur for a flexibly supported span of any size of hot and pressurized carbon steel target pipe.

The requirement that nondimensional parameters (like ma/sA where m is pipe mass, a is pipe acceleration, s is pipe axial stress and A is pipe cross-section metal area) having the most significant effect on the nonlinear dynamic behaviour of pipes must have the same values in both a scale model and a prototype system, when both are fabricated using the same material, means it must be considered that time has the same scale factor as geometries. Therefore, velocities would have the same values in both the scale model and the prototype. Also, forces would be scaled by the square of the geometrical scale factor while masses and energies would be scaled by the cube of the geometrical scale factor.

Although changes in the wall thickness-to-diameter (t/d) ratio of target pipes from the conditions used in our testing are expected to have a significant effect on the

impact behaviour of a target pipe, the magnitude of such effects cannot be estimated from our data as we studied target pipes having only one t/d ratio. However, an estimate of the effect of changing the t/d ratio of a target pipe can be obtained by using the recently reported results for 7 pipe/pipe impact tests performed at the Battelle Pacific Northwest Laboratory [3]. In these tests, 6 inch Schedule 80 carbon steel whipping pipes pinned at one end impacted the mid-point of simply supported 3 meter long spans of hot and pressurized 6 inch Schedule 40 and 80 carbon steel pipes. Because the rupture of one of Battelle's Schedule 40 target pipes was associated with just slightly more than a 30% reduction in its diameter, while none of our target pipes ruptured before reaching a 60% reduction in diameter, it seems that the magnitude of the deformation associated with the failure of an impacted target pipe may be linearly proportional to its t/d ratio, which is in agreement with Gerber's results for static pipe bending tests [4].

Comparison of the Battelle pipe impact data with our data suggests that the simple empirical relationship illustrated in Figure 10 exists between the peak percent reduction in diameter for any size of carbon steel target pipe that is impacted by a stronger whipping pipe (or one that is of about equal strength) and the energy required to deform that target pipe at the location where it is impacted. This figure uses the following generalized form for the energy (E) required to cause target pipe deformation:

$$E = \left(\frac{K}{dtD} \right) \left(\frac{DTd}{DTd + dtD} \right)$$

where K is the whipping pipe kinetic energy available to cause pipe deformation at a pipe/pipe impact location, d and t are the target pipe diameter and wall thickness while D and T are the whipping pipe diameter and wall thickness. The first term on the right side of this equation, which defines a generalized form for the whipping pipe kinetic energy available to cause pipe deformation at a pipe/pipe impact location, is consistent with the requirement that the energy ratio for two impact events is the cube of their geometric scale factor if one event is an exact scale model of the other event. The second term on the right side of the above equation, which defines the fraction of the available whipping pipe energy that is dissipated by causing target pipe deformation, is equivalent to a ratio of the energies associated with the deformation of the target and whipping pipes.

CONCLUSIONS

Pipe/pipe and projectile/pipe impact tests were performed using 2 inch Schedule 80 carbon steel target pipes that were at typical operating conditions for a CANDU reactor. In the tests involving conditions that simulated the worst pipe/pipe impact event that it has been predicted could occur for adjacent CANDU feeder pipes (when a whipping pipe has a kinetic energy of about 10 kJ just before it impacts a 2 inch pipe), no more than 26% reduction in diameter occurred for the target pipes. It was also shown that a whipping feeder pipe would have to be associated with at least five times this amount of kinetic energy before a 2 inch feeder pipe could be cracked and ruptured by the whipping motion associated with a postulated break for any adjacent parallel feeder pipes.

REFERENCES

- 1] U.S. NRC Regulatory Guide 1.46 on "Protection Against Pipe Whip Inside Containment".
- 2] J. Peech et al, "Local Crush Rigidity of Pipes and Elbows" 4th SMIRT paper F3/8, 1977.
- 3] M. Bampton et al, "Pipe-to-Pipe Impact Tests", 10th NRC Information Meeting, Oct. 1982.
- 4] T. Gerber, "Plastic Deformation of Piping due to Pipe Whip Loading", ASME paper 74NE-1.

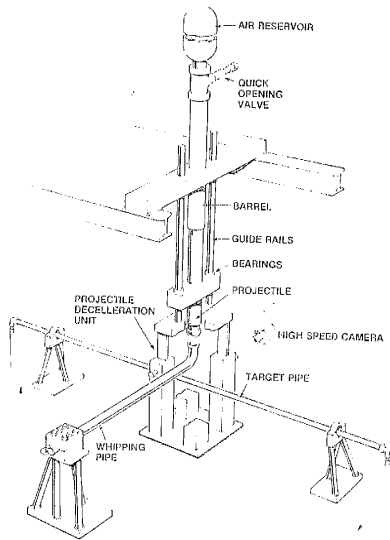


FIGURE 1: Schematic illustration of the dynamic pipe crush test rig.

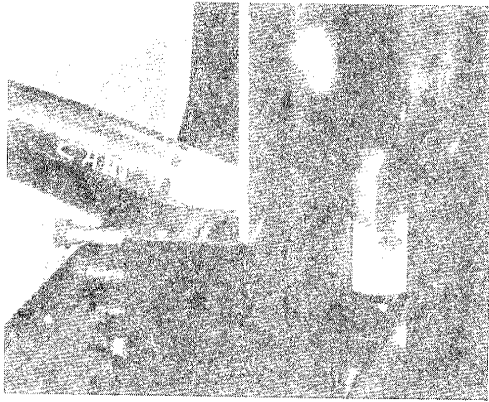


FIGURE 2: Typical configuration of the simulated whipping pipe and target pipe after a pipe/pipe impact test.

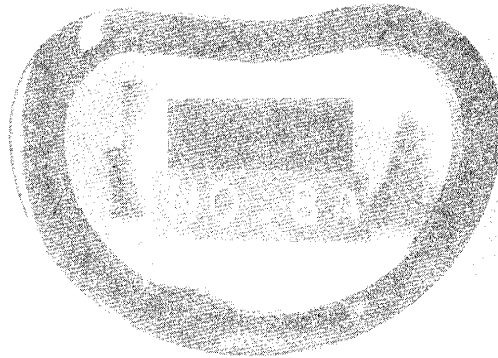


FIGURE 3: Cross-section showing the peak diameter reduction (26%) for a 2 inch Sch. 80 target pipe impacted by a 3-1/2 inch Sch. 80 whipping pipe whose kinetic energy was 10 kJ.

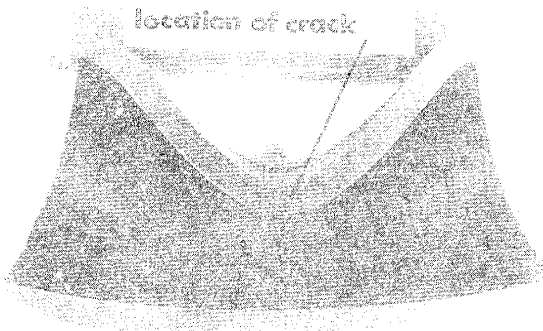


FIGURE 4: Axially sectioned 2 inch Sch. 80 target pipe showing the crack that initiated at its inside surface when impacted by a rigid projectile having a kinetic energy of 49 kJ.

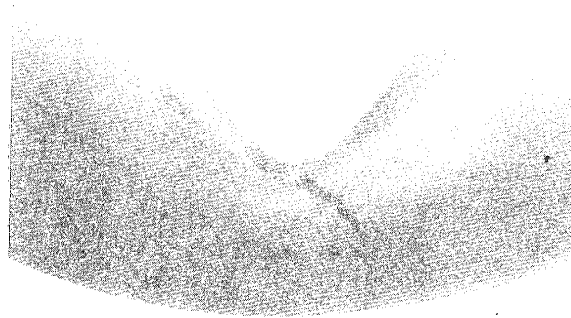


FIGURE 5: A ruptured 2 inch Sch. 80 target pipe after being impacted by a rigid projectile having a kinetic energy of 66 kJ.

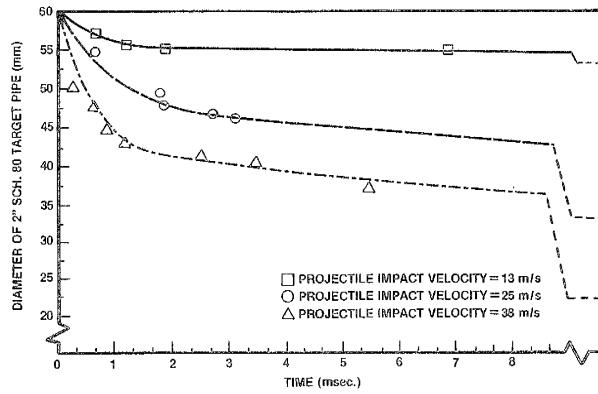


FIGURE 6: Initial deformation rate at the impact zone of 2 inch Sch. 80 target pipes in 3 typical projectile/pipe impact tests.

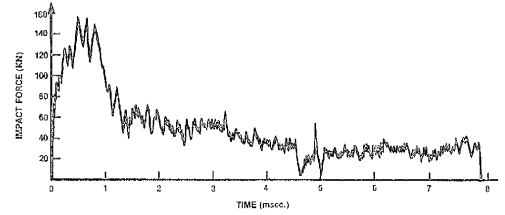


FIGURE 7: Projectile/pipe impact force for a 2 inch Sch. 80 target pipe impacted by a projectile having a kinetic energy of 66 kJ.

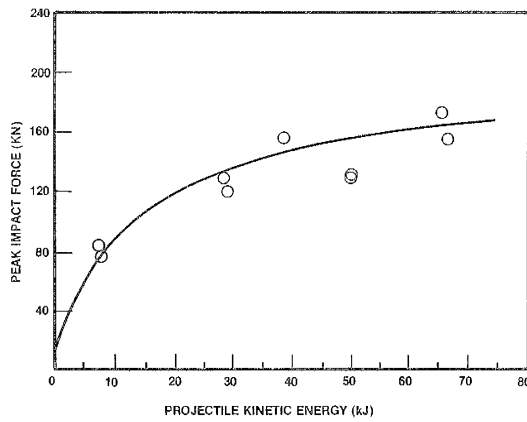


FIGURE 8: Plot of the peak projectile/pipe impact force for tests involving 2 inch Sch. 80 target pipes.

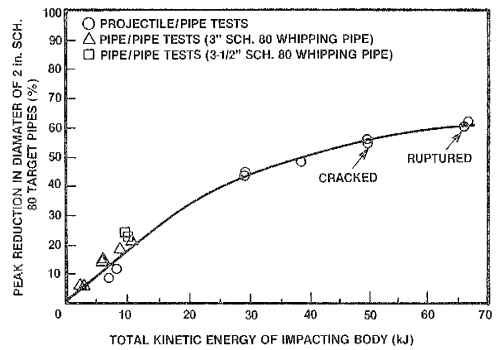


FIGURE 9: Plot of the target pipe deformation versus the total kinetic energy of the impacting body for both the pipe/pipe and projectile/pipe impact tests.

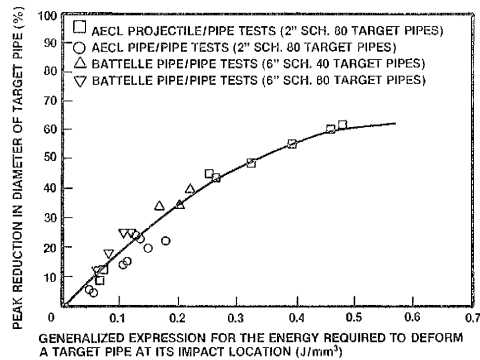


FIGURE 10: Plot of the target pipe deformation versus generalized energy for both the AECL and Battelle pipe impact tests.