Pipe to Pipe Impact Tests

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ABSTRACT

A study concerning the effects of pipe whip and pipe to pipe impact in representative operating conditions of a graphite gas-cooled reactor heat exchanger has been performed by the French Commissariat à l'Energie Atomique.

The following tests were done: pipe whip of 4" A48 grade B schedule 40 steel and impact on 2" or 4" A48 grade B schedule 40 target pipe which is simply or rigidly supported. During the test pressure, local strain, acceleration, displacement are recorded (2 high speed cameras operating at 5000 frames per second).

Measurements on the whipping phase are compared to those predicted by dynamic elastoplastic calculations using the finite element code Tedel and a good agreement is obtained.

Finally, results are discussed in terms of crushing and bending depending on the support conditions, in relation to the results from Battelle Pacific Northwest Laboratory impact tests in PWR conditions.

It is also underlined that one of the results is in contradiction with the rule from the Standard Review Plan as an impacted pipe of smaller nominal size than the swinging pipe (same schedule) presents no crack and no break after the test in spite of an important deformation.

INTRODUCTION

In the framework of safety studies on French graphite gas-cooled reactor, an experimental program has been performed by the Commissariat à l'Energie Atomique to evaluate the potential consequences of pipe whip and pipe to pipe impact resulting from a pipe rupture. First the results of the tests will be presented, then a comparison drawn with pipe whip calculations performed with a finite element code. Finally the results obtained will be discussed in relation to other experimental results published from similar programs as well as to the Standard Review Plan criteria.

TEST PROGRAM DESCRIPTION

Aim of the program

In the French graphite gas-cooled reactor heat exchanger pipes conveying water, steam or carbon dioxide gas are numerous and close together. Under the hypothesis of a guillotine break occurring on one of these pipes, the ruptured

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pipe may whip under the force applied on it by the escaping pressurized fluid. An adjacent parallel pipe could be impacted and a second break may occur consequently.

The goal of this program is to perform tests in representative operating conditions to determine what kind of damage can be expected in such a situation.

The pipe impact test facility and operating conditions

The experimental program is performed on the Aquitaine II facility. This facility has been designed for maximum operating pressure and temperature of 17.2 MPa and 340 °C respectively and has already been used for similar programs (pipe impact on rigid restraints and concrete slab [1] [2]). As shown in figure 1 the whipping pipe test section is oriented horizontally. It is filled with hot pressurized water and connected to the reservoir by a recirculating line. The target pipe is horizontal too but oriented perpendicularly to the whipping pipe. This situation represents the worst case that can be encountered between two adjacent pipes. Depending on the test the target pipe is filled with pressurized cold water or gas.

The whipping pipe rupture is initiated by an explosive device which induces a circumferential pipe break in less than one millisecond. The forces occurring at the pipe elbow at this time makes the pipe whip. The duration of the test (whipping and impact) is such that the jet force can be considered as constant during the test (pressure level at saturation conditions) except for the very first overpressure generated by the explosive device (figure 2).

Test conditions

Two kinds of tests were performed depending on target pipe support conditions. The first two tests were carried out on target pipes clamped at the ends and the third one on a simply supported pipe, with impact at mid-span in all cases. The whipping pipes were in all the tests 4 inches A48 grade B schedule 40 carbon steel pipes. The target pipe were, for tests 1 and 3, 2 inches A48 grade B schedule 40 carbon steel and for test 2 the same as the whipping pipe.

The test conditions were chosen to be as close as possible to the operating conditions, but the main parameters were considered to be the kinetic energy at impact and a sufficient gap between the two pipes (more than 1 meter). The conditions tests are summarized in table 1. They were supposed to lead, for all the tests, to a kinetic energy at impact of 40 kJ with a 30 kN thrust force on the whipping pipe supposed to be constant. The target pipes were not heated because of their relatively low operating temperature (90 to 100 °C for water pipes and less than 400 °C for steam pipes) which can be assessed not to influence their rupture strength and even to improve their impact strength.

Instrumentation

The measurements performed during the tests were:
- pressure (both pipes)
- temperature (reservoir fluid, whipping pipe steel)
- local strain (strain gage on target pipe)
- acceleration (both pipes and the ground for the last test)
- displacement (one specific transducer on target pipe plus two high speed cameras). The first camera provided a general view of the facility during the test and the second one a close shot of the impact. Both were operating at about 5000 frames per second.
TEST RESULTS

The main results of the tests are summarized in table 2. As whipping pipe operating conditions remain the same for all the tests the pipe velocity at impact is constant (39 m/s measured by displacement transducer). The angle between the whipping pipe and a vertical axis is 45°.

In fact, the real parameter of the tests appear to be the target pipe stiffness. The results confirm those of Alzheimer from Battelle Pacific National Laboratory [3]: when the target pipe is rigidly supported even if it is significantly crushed during the test the whipping pipe is deformed much more (test 1 compared to test 3). Indeed, in test 1, the target pipe diameter reduction (defined as the ratio of the maximum reduction in the outside diameter of the pipe to the initial outside diameter) is 25 % against 42 % for the swinging pipe and in test 3 these values become respectively 39 % and 8 %. These results in diameter change must be associated with those of bend angles (defined as the angle through which the pipe was bent by the impact at the point of impact). Here the target pipe bend angles are respectively for tests 1 and 3, 30° and 52°, showing the comparative importance of the two phases crushing and bending. This point will be further developed.

Figures 3, 4 and 5 show respectively the deformation of the three target pipes and figures 6, 7, 8 those of the three swinging pipes. Nevertheless the main results of the tests remain that even if great strain have been reached (probably much more than 15 %, the maximum that could be registered) no break and even no crack has been detected for any test (figure 9).

NUMERICAL ANALYSIS AND COMPARISON TO THE TEST RESULTS

An analysis of the whipping phase, identical for all the tests, has been performed with the finite element computer code Tedel (owner CEA).

These calculations are based on beam formulation and Tedel enables, with dynamic elastoplastic evaluation, the study of non-linear large deflection of pipes. The code allows calculations with a following load which is necessary because of the large swinging pipe rotation. The input parameters for the code were, except the geometrical data :

- The thrust force, F, which was supposed to be well known. Some tests had been specially devoted to the measurements of this force in a previous experimental program [2] which allowed us to determine the coefficient K in the equation :
  \[ F = K P_0 S \]
  \( P_0 \) : initial pressure 
  \( S \) : breach area

  the value K = 2.27 was obtained in the case of subcooled water. This leads for the experimental value to \( F = 30 \) kN.

- The initial gap between swinging and target pipe : 1.50 m between the two axes.

The possible points of comparison between calculations and experimental tests are :
- the whipping time between the first explosion and the impact
- the whipping pipe velocity
- the deformation of the swinging pipe at a given time and its comparison with deformations measured on the high speed camera film.

Table 3 summarizes the main points of comparison between calculations and experimental results and a comparison of whipping pipe deformation at different steps can be seen on figures 10 and 11.
A good agreement between calculation and experimental results is observed even if there is a slight shift in the results.

DISCUSSION

It is well established that the pipe to pipe impact can be characterized as occurring in two phases namely crushing (or local deformation) and bending (or global deformation or structural collapse), the final state of the two pipes being a combination of the two deformation modes which, as a first approximation, can be considered as independent [4]. The close shot film provided by the second camera permitted the estimation of the crushing phase duration (2 ms) and that of the bending phase (16 ms) for test number 2. Some pictures extracted from the film show the progression of the whole sequence (Figure 12).

It is very difficult to estimate the part of kinetic energy which is dissipated respectively in target pipe crush and bend and in whipping pipe crush and bend. It is because first the initial crush diameter change can be modified during the second bending phase and secondly the final deformed state is also dependent on the whipping pipe deformation and on the interaction between the two pipes (see on figure 4 the indents caused by swinging pipe on test number 2 target pipe). So it has been decided, in order to compare the results to those from similar programs, to adopt the definition from Alzheimer [5] of the deformation parameter. This parameter combines bending and crushing normalized effects and can be defined as:

\[
\text{deformation parameter} = \left[ \left( \frac{A D_1}{D_1} \right)^2 + \left( \frac{1}{2} \frac{A \theta}{\frac{D_1}{D_2}} \right)^2 \right]^{1/2}
\]

where \(D_1, D_2\) are diameters of target and swinging pipe respectively

\[A \theta: \text{ bend angle (radians)}\]

\[\frac{A D_1}{D_1} \text{ is normalized crush}\]

\[\frac{1}{2} \frac{A \theta}{\frac{D_1}{D_2}} \text{ is normalized bend}\]

The deformation parameter values calculated for the three tests are respectively 0.29; 0.09; 0.46. These are rather low values compared to the tests performed in Battelle PNL (up to 0.91) except for the last one. This is not surprising because tests with rigidly supported target pipes are much less severe than those for simply supported pipes. Reciprocally, swinging pipe deformation parameter is all the more important as the target pipes is rigid (0.71 for the second test; 0.59 for the first one and then only 0.09 for the third one). The three results have been presented among the Battelle PNL ones on figure 13. We can see that, though the tests are performed with a different steel, the results are consistent with the PNL ones. Crushing can be noticed to be slightly more important than bending for those tests because of small pipe wall thickness (schedule 40).

COMPARISON TO THE STANDARD REVIEW PLAN RULES - CONCLUSION

According to the Standard Review Plan [6]: "An unrestrained whipping pipe should be considered capable of causing circumferential and longitudinal breaks, individually, in impacted pipes of smaller nominal pipe size ...."

It is not the case for our tests, even in the most conservative target pipe support condition. (This means that for our safety studies margins remain even outside the deformation limit area).
A complementary program will permit a better definition of the limits beyond which a break or even a crack can occur in the target pipe in our operating conditions.

REFERENCES


<table>
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<tr>
<th>Whipping pipe (all the tests)</th>
<th>Target pipe</th>
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<tbody>
<tr>
<td>Outer diameter (mm)</td>
<td>114</td>
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<td>Thickness (mm)</td>
<td>6</td>
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<tr>
<td>Material</td>
<td>A48 grade B</td>
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<td>Length (m)</td>
<td>3</td>
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<tr>
<td>Pressure (MPa)</td>
<td>8.5</td>
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<tr>
<td>Temperature (°C)</td>
<td>277 (P_{sat}=6.1 MPa)</td>
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<tr>
<td>Nature of feeding fluid</td>
<td>Subcooled water</td>
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<td>Support condition</td>
<td>Embedded at one end</td>
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Table 1: Test conditions
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<th>Test 1</th>
<th>Test 2</th>
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<tr>
<td>Diameter reduction (%)</td>
<td>25</td>
<td>42</td>
<td>7.5</td>
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<tr>
<td>Bend angle (°)</td>
<td>30</td>
<td>25</td>
<td>5</td>
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<tr>
<td>Normalized crushing</td>
<td>0.25</td>
<td>0.42</td>
<td>0.075</td>
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<tr>
<td>( \frac{AD1}{D1} )</td>
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<td>Normalized bending</td>
<td>0.138</td>
<td>0.41</td>
<td>0.044</td>
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<td>( \frac{1/2 \Delta \theta (D1/D2)}{D1} )</td>
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<td>Deformation Parameter</td>
<td>0.29</td>
<td>0.59</td>
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Table 2: Test results

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<td>Time to impact (ms)</td>
<td>73</td>
<td>78</td>
<td>81</td>
<td>76</td>
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<tr>
<td>Maximum (m/s) vertical velocity</td>
<td>37</td>
<td>No measurement</td>
<td>30 (39 ms Displacement transducer at 45°)</td>
<td>36</td>
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<tr>
<td>Kinetic energy (KJ) at impact</td>
<td>40</td>
<td>—</td>
<td>—</td>
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</table>

Table 3: Comparison between calculation and results

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Figure 1: Test section

Figure 2: Pressure in the vessel

Figure 3: View of test 1 target pipe in the impact zone

Figure 4: View of test 2 target pipe in the impact zone

Figure 5: View of test 3 target pipe in the impact zone
Figure 6: View of Test 1 swinging pipe in the impact zone

Figure 7: View of Test 2 swinging pipe in the impact zone

Figure 8: View of Test 3 swinging pipe in the impact zone

Figure 9: Strain registered on target pipe at the opposite of the impact
Figure 10: Experimental swinging pipe deformation

Figure 11: Calculated swinging pipe deformation
Figure 12: Crushing and bending phases

Impact

2 ms after impact
end of crushing phase

16 ms after impact
end of bending phase

Figure 13: Comparison of deformation parameter calculations with ref. [5]