Mechanical Effects of Breaks on PWR Primary Pipings
Analytical Interpretation of Tests

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In the last six years, a very large program for testing the mechanical effects of postulated breaks on P.W.R. Primary Pipings has been managed in FRANCE.

This paper intends to present the benefits expected from this work in terms of qualitative and quantitative basis for further mechanical analysis.

The major simplifying assumptions dealing with the behavior of the pipes and of their supporting structures have been verified.

A complete set of tools for analysis of the pipe whip and impact have been developed and qualified.

Therefore time-dependant loads on structures and equipment, in case of a theoretical large LOCA, can be predicted with reasonable safety margins.

1. AQUITAINE II PROGRAMS

In 1976 an experimental program named AQUITAINE II was set up by a four-party group, i.e. : Electricité de France, le Commissariat à l'Energie Atomique, Framatome and Westinghouse. This program, already presented in ref. [1] , was intended to generate a great number of physical data related to the behavior of primary pipes and supporting structures in case of a large pipe break.

Later on, two more programs, with the same name, were managed by three French partners of the original group. The first one was a limited series of tests and was intended to complete the coverage of all possible geometrical configurations encountered on actual primary loops.

The second and final one, which is the main subject of this paper, has been an interpretive analytical work on all the data already gathered. These studies were made possible by the significant progress in structural analysis computer programs in the last few years : it allowed development of an original procedure of analysis which can handle the non linear, large displacements and elastoplastic aspects of the problem.

2. TESTS PERFORMED

French safety authorities require that conventional breaks be postulated on PWR primary pipings and that their mechanical consequences be taken into account in the design of equipments and supports as faulted loading conditions.

The corresponding theoretical breaks on a French standard primary loop are shown on fig.2 : six of these breaks are double-ended and one is a longitudinal split. Methods for determination of types and locations of breaks are derived from usual American practice.

Some tests in the AQUITAINE II program intend to reproduce, at reduced scale of approximately 1/10, the actual geometrical configuration for these postulated breaks. Other tests are more generic and were used for physical understanding.

All performed tests are presented on fig. 1, along with their relation to actual postulated breaks. The same figure shows also the correspondence with the technical papers given in reference. Complete description of the experimental program parameters can be found in ref. [1] and [3] .

3. STABILITY OF BROKEN LEGS

3.1. Straight pipes

When a double ended break (no.6 on figure 2) is postulated on the cold leg, near the outlet nozzle of the primary pump, no lateral displacement of the pipe is taken into account : thus no lateral stop is provided.

This assumption was originally based on a buckling analysis, with axial and flexural loads applied at the break.

In order to justify this analysis, a series of eight tests has been performed, the parameters of interest being the slenderness ratio ($\frac{L}{D}$) which varied from 7 to 15 and the applied initial moment loading.

When taking into account conservative assumptions about initial thermal moment loadings, both tests and analysis give a critical slenderness ratio of about 15. Since the ratio on actual PWR loop is much lower, no lateral displacement of the cold leg is to be expected.

3.2. Cross-over leg

Three double-ended breaks are postulated on cross-over leg (no. 2, 4, 5 and 8 on figure 2). The designed restraints are only efficient in the plane of the pipe. Two tests were performed on this geometry and no significant out of plane displacement occurred. Other tests on "S" shaped pipes gave the same result.

It must be pointed out that even with much larger displacements, (see ref. [9]) the lateral stability of the whipping pipe is always proved.

4. LONGITUDINAL SPLIT

4.1. Tests

Only one longitudinal split is to be postulated on the primary loop. According to regulatory position, its length is stated to be two diameters. Previous tests and analyses (ref. [2]) have already shown that such splits could not remain stable : the maximum possible length for stability would be around 1.3 meter.

In order to get more data on the behavior of such splits, two tests were performed in the early stages of AQUITAINE II program. Tests sections, presented on fig.3, were straight pipes between two capacities, with two-diameter longitudinal splits. The differences between the two tests were :

- the position of the split with respect to middle span,
- the two guides, on test section 2, which simulate rigid anchoring.

Two very different behavior were observed :

- Test 1 : the split propagated longitudinally until disappearance of the loading (jet force). Overall deflection remained small (see fig. 5).
- Test 2 : after a certain amount of longitudinal propagation, the crack deviated circumferentially. The pipe was finally completely torn off on both sides and a piece of approximately 500 mm long was thrown away. Deflections of remaining pipes were large.

4.2. Interpretation of tests

For interpretation of such tests, we started from a basic assumption, which is that the direction of crack propagation is highly dependant on uncracked stress field in the pipe, and that mode I is physically preferential.

Therefore, the method is to evaluate the ratio of circumferential versus axial stress in the pipe, using simplifying assumptions for the kinematics of crack opening. Axial stress is mainly developped when plastic deflection becomes significant, that is when the flexibility of the capacities is isolated (test 2).

Final results are shown on fig. 4 for test 2 : it shows that axial stress overcomes circumferential stress, after a certain amount of time, which can be satisfactorily compared with experimental data.

4.3. Extension to actual primary piping

The same analysis was then performed for the worst possible locations on actual primary loops : these cases were chosen to be more conservative than the one selected after safety

analysis (i.e. no. 7 on figure 2). This study clearly showed that there is no possibility of inverting the ratio of circumferential versus axial stress of the actual pipes due to the compliance of the complete system, including the supports.
Therefore, we can conclude that a two diameter longitudinal split, placed at any location of the primary piping, would certainly be unstable, but that the crack propagation would remain longitudinal, and would stop as the jet force decreases.

5. PIPE WHIP ANALYSIS

Many tests involving pipe whipping have been performed with many different geometrical parameters. Almost all tests were recorded with high speed camera (5000 frames per second). These test data have been compared with analytical results (as in ref. [1], [4] and [6]) obtained with TEDEL computer program (ref. [12]), which main features are :

- f.e.m. formulation of engineering beams model,
- dynamic analysis with direct integration,
- elastoplastic analysis with global model of plasticity,
- geometrical non linearities handled by updated Lagrangian formulation.

For all tests, analytical results are in good agreement with experimental data, but for a 10 to 15% over estimation of pipe velocities.
Since strain rates during pipe whip are moderate (about $5s^{-1}$), their influence on mechanical characteristics can be neglected in the analysis.
Two types of deformation of the whipping pipe were observed, in relation with the compliance of the test section :

- for long pipes ($L/D \geq 10$), with concentrated mass at pipe end, plastic strain is uniformly distributed along pipe length,
- for short pipes ($L/D \leq 5$), high strain region is limited and localized in the vicinity of the flange (see fig.6).

For analytical purposes the high strain region can be considered as a perfect plastic hinge.
In case of plastic hinge two different behaviors of the pipe have been observed :

- when ovalization of the pipe is possible, the pipe collapses without crack,
- when the pipe cannot ovalize and rotation is large the outer fibers of the pipe are torn off during bending.

Tearing off has been obtained for one test, with a very short test section. (.17 m) built-in the nozzle of the pressure vessel. Same type of ruin is shown under static bending in ref [10].
This configuration has been successfully analyzed using ultimate strain formulation.

6. IMPACT

Two types of impact tests have been performed :

- impact on rigid concrete blocks, mounted on springs, in order to evaluate the rate of energy transferred to the impacted structures,
- impact on a rigid plate, with load cells, in order to measure the time variation and the maximum value of the applied load.

These tests have shown that impact duration is low (2 ms) and that the transfer of energy to the impacted structure remains very limited (< 5%).

The data thus generated have mainly be used for adaptation and qualification of an analysis procedure, which is as follows :

- local behavior of the pipe, in the vicinity of the impact, is analized through static elastoplastic shell formulation using either TRICO (ref. [11]) or TITUS (ref. [13]) : typical load deformation curves as given by static experiment (ref. [6]) and given by TITUS code are compared on fig. 7. In case of impact, the characteristics of the material which are used in the analysis should take into account the service temperature and the dynamic Young's modulus,
- the pipe whip is analyzed as said in paragraph 5 up to the time of impact ; then the local behavior of the pipe is simulated by a special compressive non-linear element having a law (σ,ε) deduced from the previous shell analysis.

This procedure has been used for analytical simulation of some tests and proved to give very accurate results in terms of time dependant load on the supporting structure. Other experiments (see ref. [9]) with much larger gaps, will be analyzed with the same procedure in order to extend the qualification domain of the method.

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FIGURE 1 : COMPLETE AQUITAINE II PROGRAM.

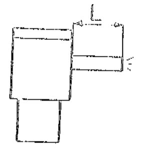
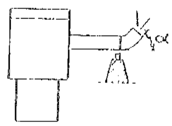
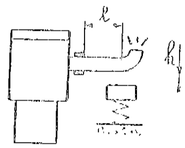
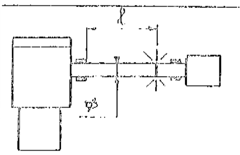
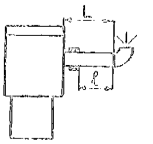
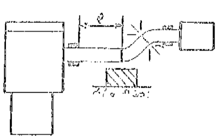
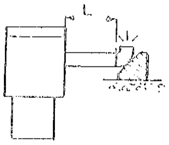
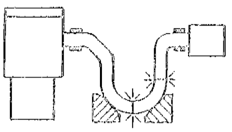
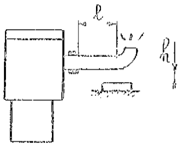
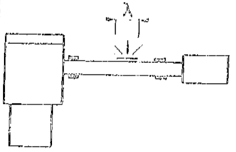
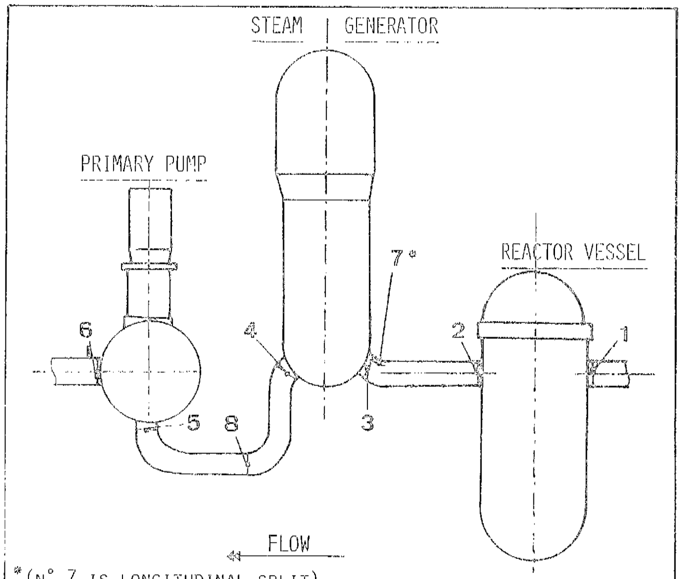
NR OF TESTS		REF. BREAK (FIG.2)	REF. PAPERS	NR OF TESTS		REF. BREAK (FIG.2)	REF. PAPERS
16		1 2 6	[1] [3] [5] [8]	3		3	[3]
6			[1] [4] [5] [6] [9]	8		6	[1] [3]
3		3 4 5 8	[1] [10]	3		4 5 8	[3]
5			[1] [4] [6]	2		4 5 8	[1] [3]
2			[1] [4] [5] [6] [7]	2 2		7	[2]

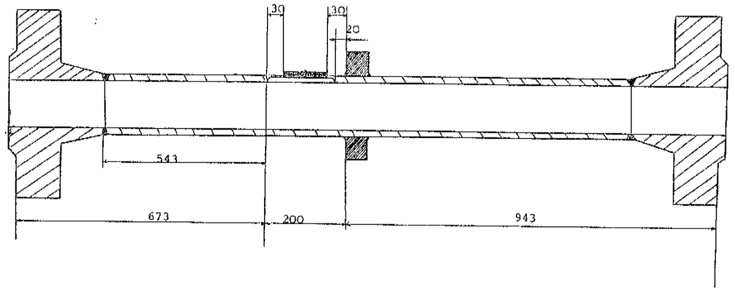
FIGURE 2 : POSTULATED BREAKS ON A PWR PRIMARY LOOP



*(N° 7 IS LONGITUDINAL SPLIT)

FIGURE 3 - TEST CONFIGURATIONS

TEST 1



TEST 2

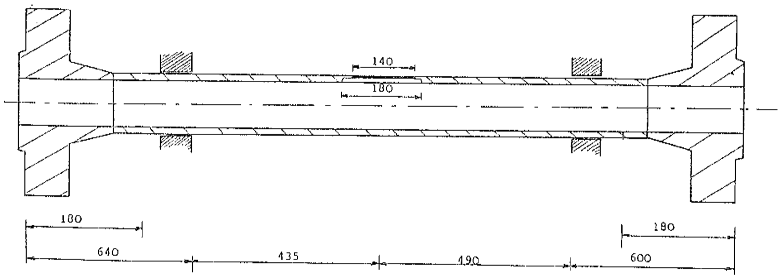


FIGURE 4 : VARIATION OF AXIAL STRESS

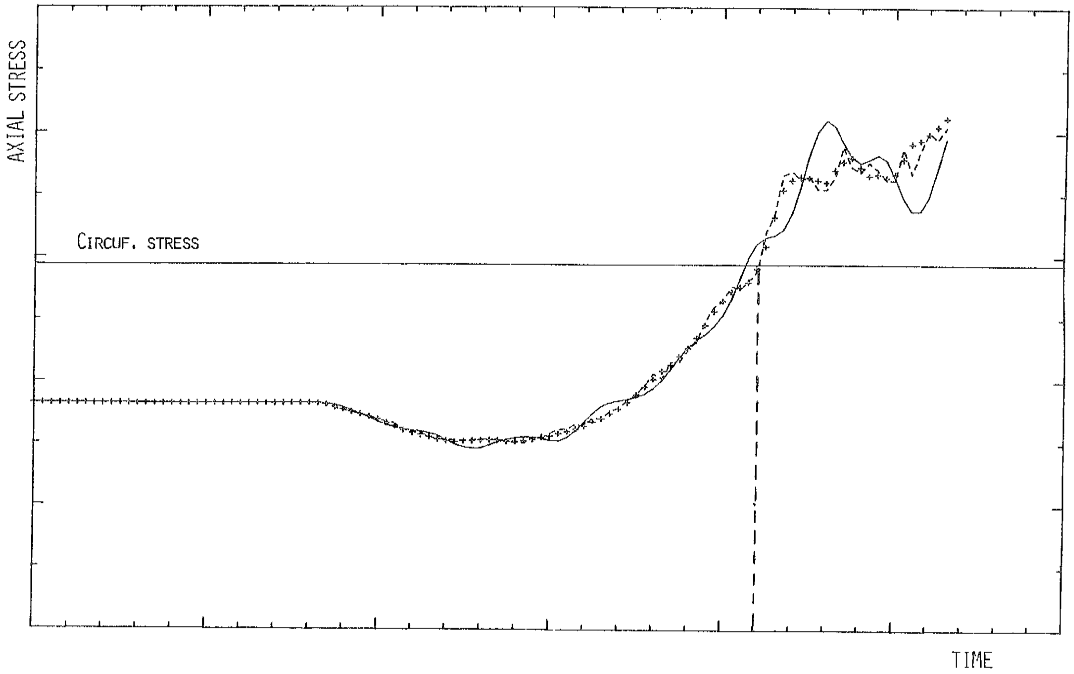


FIGURE 5 : LONGITUDINAL PROPAGATION OF CRACK
PIPE AFTER TEST 1.

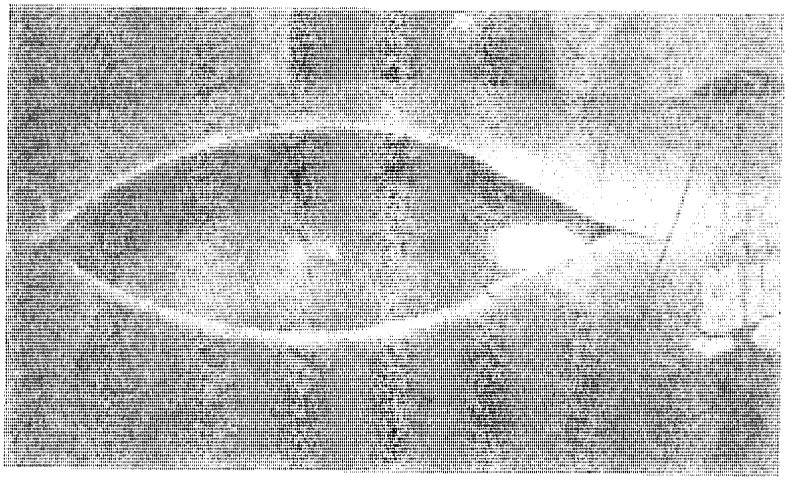


FIGURE 6 : CALCULATED STRAIN FOR SHORT PIPE WITH
RIGID FLANGE.

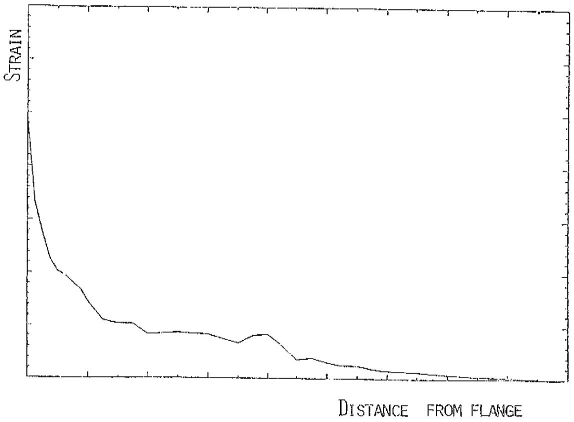


FIGURE 7 : LOAD/ DEFORMATION CURVE FOR 90°
ELBOW (STATICAL)