資料第4－2－3号

講演参考資料

FRENCH DESIGN PRINCIPLES AND R&D RELATED ACTIVITIES TO ENHANCE SODIUM HEAT TRANSPORT SYSTEMS SAFETY

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The 4th Meeting of The Special Committee on Fast Breeder Reactors
May 8, 1997

FRENCH DESIGN PRINCIPLES AND R&D RELATED ACTIVITIES TO ENHANCE SODIUM HEAT TRANSPORT SYSTEMS SAFETY

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INTRODUCTION

Today, 95 % of the world nuclear generating capacity is provided by water-cooled nuclear reactors, PWRs, BWRs, VVERs, HWRs, and RBMKs. Most of the remaining 5 % comes from gas-cooled reactors, and only a handful of reactors, throughout the world, are cooled by liquid sodium.

As a consequence, most reactor specialists have a rather shallow knowledge of sodium and sodium circuits, and for the public at large, sodium is, at best, a vague memory of chemistry lessons in high school : a nasty material which reacts violently with water.

Public reactions to last December sodium leak in the Monju reactor gives a measure of the lack of knowledge and abundance of distrust about sodium. The general feeling was : a sodium leakage is a very rare and very severe event. Both assertions are wrong : a number of sodium leaks have occurred since liquid-metal cooled reactors operate, but none has had severe consequences.

Used as a coolant, liquid sodium does induce a number of specific problems : operation at high temperature, possibility of sodium - water reactions in the steam generator units, consequences of sodium fires in case of a leak, and risk of corrosion by sodium compounds after intervention. But sodium does exhibit significant advantages, like low pressure, high thermal inertia, high boiling temperature and good thermal conductivity.

In an effort to dispassionate the topic, this papers shows the experience we have on the actual problem associated with sodium cooling, and summarises the R and D we carry out, in France, to alleviate these problems.

I. DESIGN OF SODIUM CIRCUITS

A. STRUCTURAL MECHANICS

Due to the operating conditions : high temperature, low pressure, the significant mechanisms in damage of structures are : thermal creep, fatigue, and combination of creep and fatigue, buckling ; secondary stresses are important in mechanical loading. Thermal striping due to temperature fluctuations of Na flow in contact with structures is another potential damaging phenomenon. The situations to consider are : normal operating conditions, including thermal transients, and accidental ones among which the Na/water reaction in a steam generator unit and a seism are the more important.

A part of the R&D program is thus devoted to establish for the above mentioned items a set of rules, validated on specific experiments, avoiding too much conservatism [1].

B. MATERIALS

The main criteria structural materials must answer are the ability to operate at high temperature and in sodium environment, during very long periods ; this led to choose austenitic steels for all components, except for the steam generator bundle for which ferritic steels may provide more economic design. In normal conditions, the materials are compatible with sodium ; but careful attention must be paid to avoid to meet condition of corrosion by compounds as soda or sodium oxide.

The R&D effort is mainly devoted to the study of ageing phenomena - structural evolution, long-term properties such as creep, which proved to be of paramount importance to ensure possibility of long term operation of plants.

C. WELDED JOINTS

Most of the defects proved to affect welded zones. An important R&D program is devoted to the knowledge of their specific problems : micro structure and its evolution, mechanical properties, crack propagation, and to develop adapted rules. Residual stresses due to welding can play an important role in local loading ; it is necessary to lower them, and to be able to calculate them.

D. ORGANISATION OF THE CIRCUITS

The geometrical arrangement of the circuits contributes to their reliability and safety. The comparison of Superphenix and European Fast Reactor (EFR) secondary loops (fig 1) is an example of possible improvements. Besides the search for compactness and simplicity, it is necessary to carefully design bearing points, aseismic shock absorbers, expansion lines, which avoid local stress accumulation. It is also important to foresee interventions and take all disposition to facilitate inspection, repairs... and return to safe operation.

E. QUALITY OF DESIGN AND REALISATION

The greatest care must be applied to quality. All constituents including auxiliaries, are important and must be carefully studied ; there exists no negligible details. The consequences of any evolution in design or/and operational conditions must be carefully assessed. A high level of quality during realisation must be insured : conformity of materials to specifications ; conformity of construction, especially of welded joints ; very good fitting when assembling structures ; careful examination of derogations ; inspections and tests before start-up. It is important to characterise the fabrication defects, because they can induce problems by evolution in operating conditions.

II. SODIUM RISK ASSESSMENT - LEAK BEFORE BREAK APPROACH

A. GENERAL PROCESSES

The safety analysis has to consider the consequences of defects leading to loose the tightness of circuits. To consider a total circumferential breach, as for PWR, does not seem realistic, because in fast reactors there is no pressure acting as primary load, and leads to heavy solutions ; this is the case for Superphenix where two years works were necessary to make the plant able to face the assumption of total breach of a main secondary pipe.

The leak before break approach (LBB) is developed to provide a satisfying answer : it aims to demonstrate that a hypothetical defect evolves towards a detectable leak, the defect remaining stable under an accidental loading. Phenomena like thermal striping, corrosion, material evolution are not taken into account ; the LBB approach assumes they are avoided. Key issues are : efficiency of leak detection systems ; ability of rupture mechanics to deal with defect behaviour.

B. SODIUM LEAK DETECTION SYSTEMS

A performing system must detect small leaks, rapidly, and give no spurious alarms. An extensive R&D program conducted on a specific loop, Futuna, allowed improvements of detectors (electrical wire and spark plug type), development and qualification of alternative devices ; the heat insulator, directly in contact of the pipes, plays a predominant role in the flow of escaping sodium, and thus in the performance of detectors ; its reaction with sodium leads to a specific kind of electrochemical corrosion (fig 2) [2] . All these phenomena are in course of modelisation. Further developments will include confirmation of the existence (for instance by signal processing) and the extent of a leak after detection.

C. FRACTURE MECHANICS

The objective is to obtain validated methods of analysis of the nocivity of defects in structures under operating conditions. Creep and creep-fatigue are predominant phenomena ; an extensive R&D program is conducted in CEA to establish rules for initiation and propagation of cracks, including tests on samples (CT) and on representative mock-up of pipes ; in some experiments solicitations representative of seism and thermal shocks are added.

The evaluation of the breach area, of the sodium flow rate across the breach, coupled with models of sodium progression outside of the breach, should contribute to the description of detection performance.

D. OTHER ASPECTS OF LEAK BEFORE BREAK APPROACH

To ensure that no fabrication defect greater than the "LBB" defect exists, a high level of quality, and the demonstration of this level, are a complement of the LBB approach. It is necessary to be able to follow the evolution of existing defects identified during fabrication, or to demonstrate that no non-admissible new defect appeared. In service inspection capability is another important complement of the LBB approach.

III. SODIUM FIRES

Escaping sodium can burn when coming in contact with air ; the consequences on the plant depend on the nature of the fire (pool- or spray-) and of its extension. Spray fires, where the sodium is divided, are more harmful and have to be considered in dimensioning. An extensive R&D program is engaged to describe them and calculate the thermal and mechanical loading they induce on surrounding structures. In support, experimental sodium fires were made in specific facilities such as Esmeralda (up to 37 tons for pool fires and 230 kg/s for spray fires) in France or Fauna in Germany. Simpler tests allowing parametric studies and extrapolation to higher flow rates use simulation by hot water jets in air in the Airbus facility (fig 3).

Fight against fire uses preventive devices as smothering pans isolating the sodium from oxygen, or partition of rooms, or in some cases inert gas ; special extinguishing powders are efficient against pool fires but not against spray fires.

IV. REVIEW OF FAST REACTORS OPERATING EXPERIENCE

A. INVENTORY OF SODIUM LEAKS

An extended experience is available from fast reactors having run all over the world. For European and Russian reactors about 125 loss of tightness events are reported from minute oozing to actual fires ; no leak occurred in Joyo ; FFTF and EBR2 report quite satisfying operation of sodium transport systems, although EBR2 experienced a severe sodium fire during maintenance (Na « plug » unfrozen)

Very few leaks affect the primary circuit. The majority concern secondary pipes, and occur almost always on welds. Two leaks occurred on large vessels : Superphenix storage tank and PFR steam generator units vessel. In most cases, leaks did not induce fires. The consequences on plant availability are quite variable : from negligible delay to several months.

B. SOME SIGNIFICANT EXAMPLES

1. Superphenix thermocouple thimbles

In July 1985, before first criticality, a micro leak occurred in the tightness weld of a thermocouple thimble, on an steam generator unit sodium outlet pipe ; some days later, oozing was discovered on a similar thimble. The analysis showed that for the affected thimbles the amplitude of vibration was high, due to an excitation by the eddy flow frequencies. The solution consisted in shortening the thimbles to increase their natural frequency. This modification was made on 37 thimbles of the secondary loops.

2. Leak of Superphenix storage drum tank

This leak of the storage drum tank, which involved about 20 m^3 tons, led to 20 months unavailability. The cause was attributed to hydrogen embrittlement of the ferritic steel 15Mo3, enhanced by the residual welding stresses. This illustrates the importance of the choice of material , the role of welds, and the beneficial action of the safety vessel concept

3. Phenix secondary circuit expansion tank [3]

During inspection in May 1993, defects were discovered on a discharge area of the expansion tank of circuit n° 3 ; at this place, a pipe brought sodium at 550°C in the sodium of the tank, at 350°C. The cracks affected both base metal and welds (fig 4a) ; the deepest were in the welds and one went through the wall. The material was 304 stainless steel (SS). This led to extensive repair of the tank ; a part of the wall was replaced. The design of the discharge pipe was modified to move the jet away from the wall and reduce the flow. This incident illustrates the damaging potential of thermal striping, and the importance of a careful design to avoid its initiation.

4. Defects on 321 stainless steel

Phenix - A non destructive inspection program conducted on Phenix secondary circuits from 1989 revealed a cracking phenomenon (fig 4b) on the parts made of titanium stabilised 321 SS ; this appeared to be a generic problem . Similar cracks were observed on welds of buffer tanks also made of 321 SS, one of which went through the wall. The leak which occurred in 1986 on Phenix n°3 reheater inlet tee had the same cause ; as it was not discovered rapidly, an extensive typical corrosion by a mixture of sodium and insulator material was observed on the outer surface.

PFR - The same phenomenon affected the containment vessel of a steam generator unit, made of 321 SS, in 1987,88 and 90.

The involved mechanism is a delayed cracking due to welding residual stresses applied on a material embrittled by carbides precipitation. This illustrates the importance of knowing ageing phenomena, to make a correct choice of materials for given operating conditions. The consequences may be important : for Phenix, the decision was taken to replace all 321 pipes by 304 ones. Local repairs were possible for the buffer tanks, the tee and PFR vessel.

5. BN 600 sodium leak and fire

In May 1994, during a programmed shutdown, it had been decided to change a valve on the dump circuit of a heat exchanger ; a leak occurred because the presence of a gas lock in the upper leg of the line had prevented to realise a correct solid sodium plug. A pool fire resulted, which lasted 9.5 h, the involved quantity of sodium being estimated at 1.3 m^3, several tens of kilograms of which burnt. The fire was fought by putting metal trays under the leak, and covering with extinguishing powder, and the consequences were minimised. Repair of the affected loop was completed two weeks after the incident.

This shows the necessity of very careful definition of procedures, even for current intervention, and the ability to limit the consequence of fires following leaks.

C. OTHER EVENTS

1. Sodium/water reaction

BN 350 - This plant experienced several sodium/water reactions ; the most important occurred in 1975 ; pressurised water feeded the affected evaporator during some minutes after the initial leak ; about 800 tons of water came in contact with sodium, and 120 tubes were damaged. The steam generator units was removed and replaced in 1978 by a new type. It is worth to note that even with such an important incident the rest of the plant was not affected and further operation remained possible.

PFR - In 1987, during full power operation, a reaction occurred caused by vibration induced fretting of a tube against the central duct of the superheater. 40 tubes failed, with 5 to 10 cm long breaches, and 70 were deformed by overheating. In spite of the extent of the damages the plant was operational again in a reasonable time. The incident revealed a problem of design (tube wear by fretting) and confirmed that unavailability or bad operation of components (here hydrogen detection in sodium was not in service, and a frozen dump line led to a sodium pollution) worsen the consequences.

2. Sodium pollution

Air pollution in Superphenix - In June 1990, an air ingress due to a leak on an argon activity measurement circuit polluted the sodium and led to reactor shut down. By operation of the integrated purification circuit the purity was recovered (1 ppm oxygen) at the end of the year. There were no detrimental consequences on the plant, nevertheless the plugging meter indications remained difficult to interpret because of the existence of compounds (ternary oxides) formed at high temperature.

Oil pollution in PFR - A lost of about 35 litres of oil in the primary sodium led to 18 months unavailability in 1991-92.

These two incidents illustrate the necessity to maintain the sodium purity; and the great potential effects of apparently minor causes of incidents concerning the primary sodium.

CONCLUSION

The design of sodium heat transport circuits must take into account specific problems due to the characteristics of fast reactor circuits ; R&D is necessary to establish well validated design rules avoiding excessive conservatism. The leak before break approach is essential to deal with the consequences of defects, and requires also important R&D developments. The quality of realisation, the possibility of in service monitoring are major contributors to the safety of circuits.

The review made in this paper of various incidents occurred in fast reactors operating in the world illustrates the fact that they never had severe safety consequences. After delays of varied lengths, all reactors have been repaired, and allowed to resume operation.

Further experience will progressively reduce further both the number of leaks and their consequences.

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Information on the incidents described in this paper may be found in the proceedings of the following conferences and meetings :

International conference on fast reactors and related fuel cycles, Kyoto, Japan, October 1991

Sodium cooled fast reactor safety, Obninsk, Russia, October 1994

IWGFR, Status of national programmes on fast breeder reactors, 1990,91,92 and 93

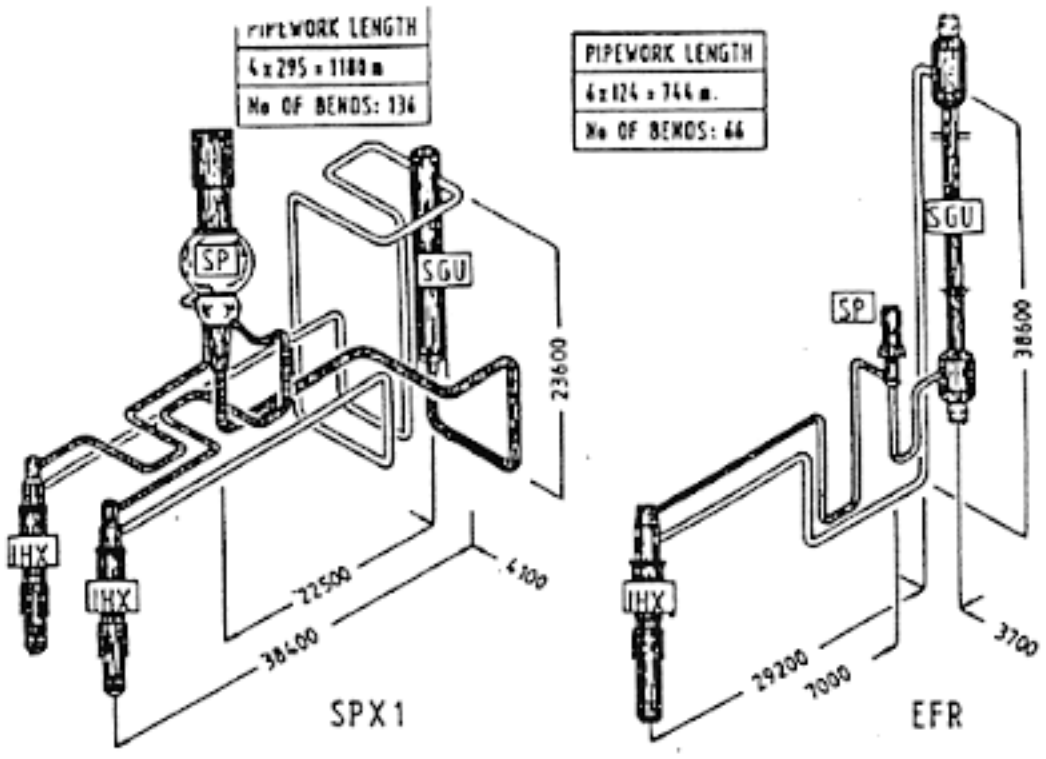


Fig. 1 Comparison of the secondary sodium loops

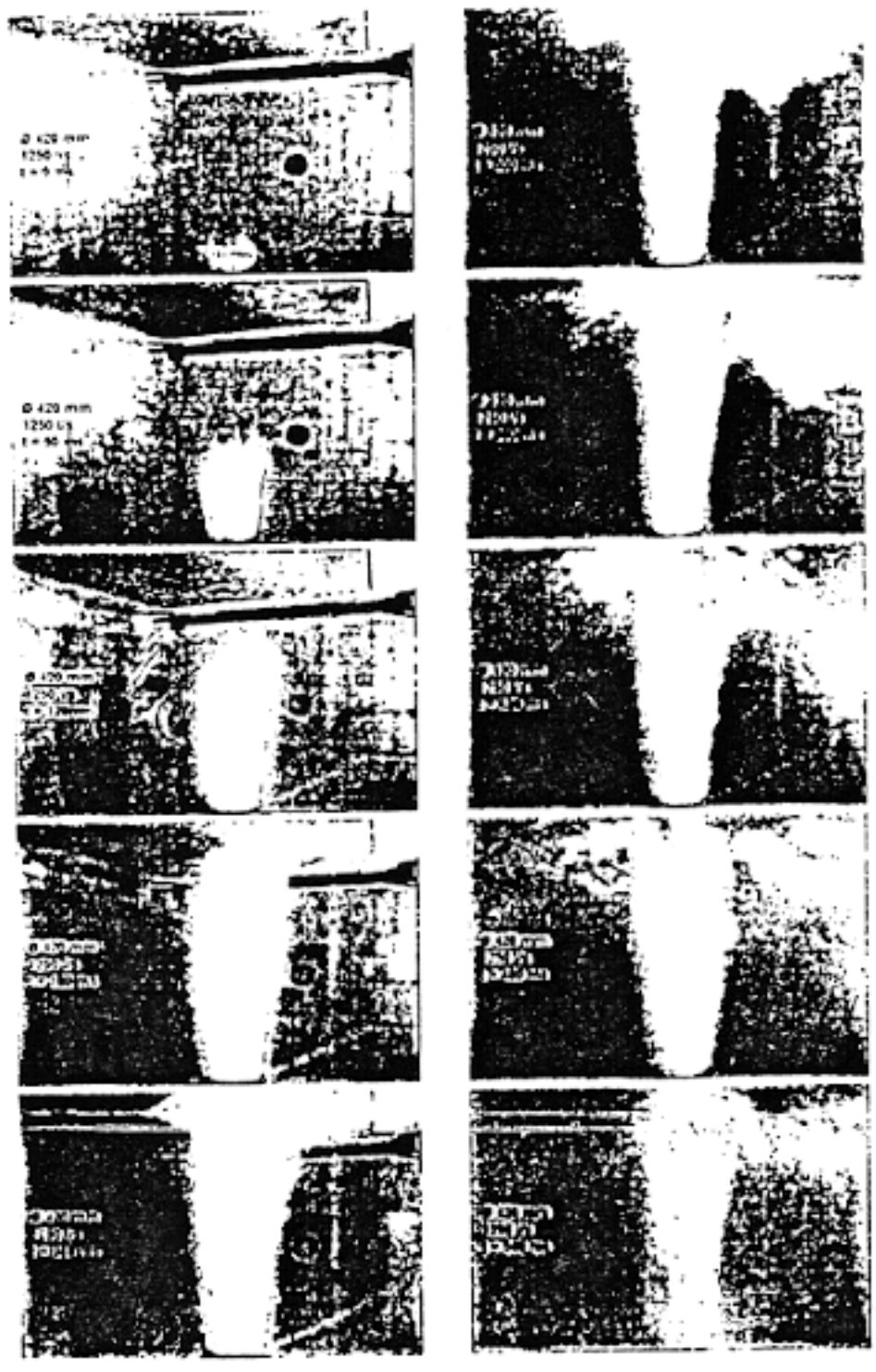
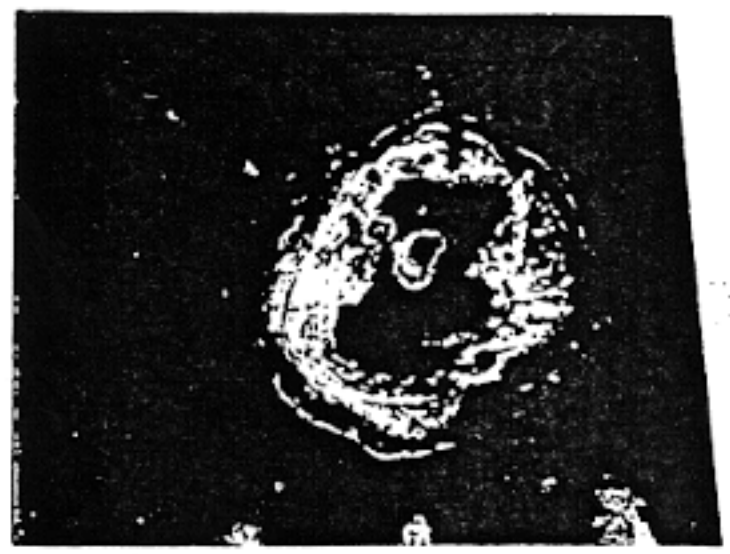


Fig.3 Simulation of a sodium fire in the AIRBUS facility



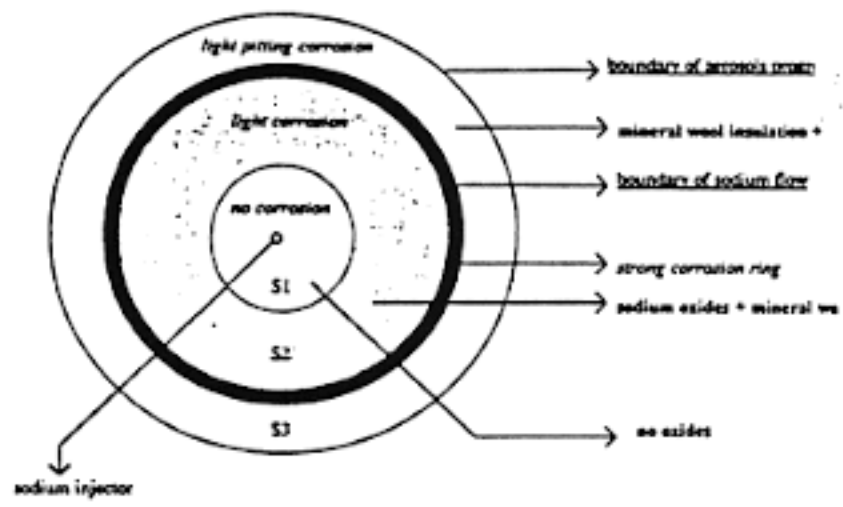
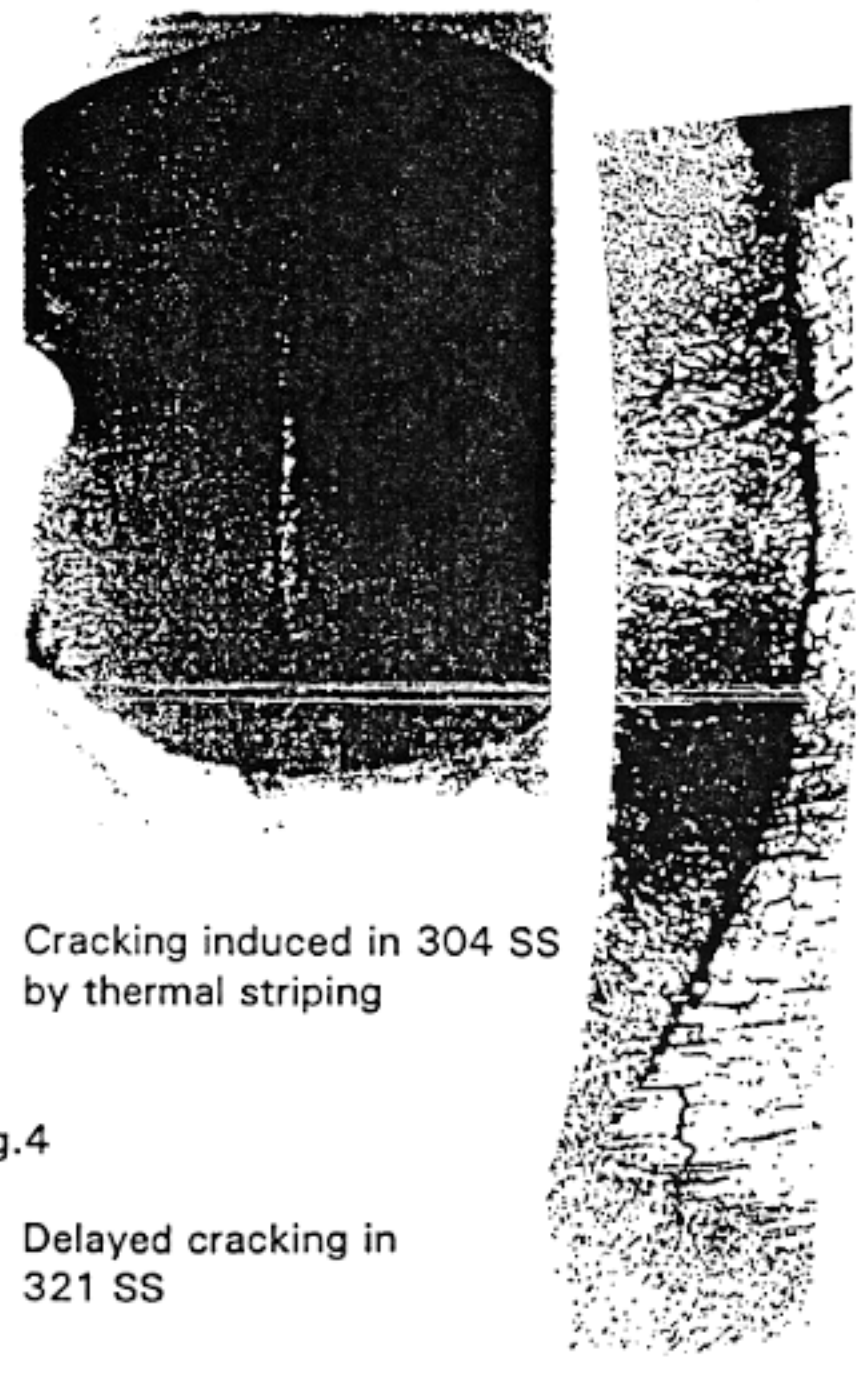


Fig. 2 Futuna sodium leak test
Observation and modelisation



a) Cracking induced in 304 SS by thermal striping

Fig.4

b) Delayed cracking in 321 SS