# PRELIMINARY SURVEY OF RELIABILITY ANALYSIS OF LMFBR PRIMARY COOLANT SYSTEM PIPING

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## SUMMARY

It is one of the significant problems in the safety evaluation of the loop-type LMFBR (Liquid Metal Cooled Fast Breeder Reactor), whether the severance of the FBR primary coolant system pipe should be postulated as an initiating event of the Design Basis Accident as in the case of LWR (Light Water Reactor). The low internal pressure of the LMFBR primary coolant system may reduce the probability of the occurrence of the severance of its pipe in some degree compared with the LWR primary pipe, and it is one of the motives to raise this problem. On the other hand, in LMFBR, the temperature difference between the hot leg and the cold leg is large and the operating temperature of the hot leg pipe is considerably higher than that of the LWR primary pipe. It is a matter of course that the design criteria cope with the difference in these operating conditions, nevertheless, the hot leg pipe of LMFBR should be considered to have more potential failure chances from the standpoint of the evaluation of the integrated reliability, because the experiences to design, fabricate and operate the nuclear power pipes in this high temperature range, where the materials show creep behavior, are very few.

The author reports the prelimary survey of the reliability analysis of the cold leg pipes of the primary coolant system of the 300 MWe class loop-type sodium cooled FBR, where the occurrence of the severance is significant in the view-point of the safety design of the FBR but the creep behavior of the materials could be neglected.

The first part of the survey is that of the present status of the operating conditions, design method, material, fabrication, inspection and quality assurance of the piping system, to pick up the essential values in the probabilistic evaluation of the severance.

The second part of the survey is the trial to draw the fault tree to the severance of the piping system which consists of two stages. The first stage is the probabilistic evaluation of the potential "damaged conditions" which are caused by the low-cycle fatigue etc. throughout the life time of the reactor. The second stage is the evaluation of the occurrence of the severance when the extreme loads with low probability are loaded to the piping system in the "damaged conditions."

1. Introduction

The author proposes the following procedure to establish the system to analyze quantitatively the structural reliability of the cold leg piping of the primary coolant system for the loop-type liquid metal cooled fast breeder reactor (LMFBR).

(First Step)

To analyze probabilistically the potential "damaged conditions" of the piping system throughout its life time which are caused by failure mechanisms such as the low-cycle fatigue, and cannot be detected by the in-service monitorings and inspections.

(Second Step)

To analyze probabilistically the degree of the fractures which are caused by the extreme loads which have the low probabilities of occurance to be loaded on the piping system of the "damaged conditions".

To make the start of the discussion of the analysis method for these procedures, the author sets the model of the piping system which is as simple as possible to simulate the characteristics of the cold leg piping of the LMFBR primary coolant system. The discussion should be extended to the real piping systems in the future.

2. Model of Piping System

In the structural design of the coolant systems of the LMFBR in Japan, the aseismic design consideration usually makes the reactor vessel, the intermediate heat exchanger and the main pump casing fixed to the building. The pipings between these large components are laid out in the complex fitures using many 90° elbows to absorb the thermal expansions, and are attached many sets of the dumpers which are required by the aseismic design. The schematic view of the primary coolant system pipings of the 300 MWe class loop-type LMFBR is shown in Fig. 1. The usual fabrication procedure of the cold leg piping of those is shown in Fig.2. It is not so easy to simulate the piping system by the simple model, but the author tried to plan the model of the piping system shown in Fig.3 and Fig.4. Fig.3 shows the lay-out of the model piping system which is simple three dimensional piping. Though in the neighborhood of the inlet nozzle of the reactor vessel in the real piping system (Fig.1), there are at least two elbows in the x-z plane, the model has only one elbow in x-z plane in the neighborhood of the model of the nozzle N-1 (Fig.3) which simulates the inlet nozzle of the reactor vessel. Then in the model piping, the torsional moment should be somewhat exaggerated in the model. The author should have the room to check the suitability of the modeling. Also, the modeling of the attachment of the dumpers is tentative and not checked by the aseismic design analysis. Fig.4 shows the trial to divide the model piping system to structural components based on the discussion of the fabrication procedures.

3. Analysis of the "Damaged Conditions"

The analysis procedure of the "damaged condition" of the model piping system consists of two phases. The first phase is the analysis of the propagation of the typical cracks (the axial crack and the circumferential crack) in the typical components loaded the typical stress fields with the aid of the linear fracture mechanics method and the reliability engineering, where the main process of the crack propagation is assumed as the low cycle fatigue. The second phase of the analysis is the estimation of the "damaged conditions" of the other components based on the typical components through the "quality indices" and the "stress field indices".

3.1 Quality Indices

The structural components of the model piping system are shown in Fig.4, where the components to be analyzed are 51 components from WC-1 which simulates the weld joint of the inlet nozzle of the reactor vessel to WC-12 corresponding the weld joint of the outlet nozzle of the pump casing. The functions of the "quality indices" is to make the grades of the components from the view point of the quality concerning the "primary fault conditions".[1] (The effects of the "secondary faults conditions"[1] are to be accounted in the analysis of typical "damaged conditions" in the typical components.)

The cracks to be analyzed are assumed to be the axial crack and the circumferential crack. The quality indices for the resistivity to the propagation of the axial crack is demoted by QL, and the qulity indices for that of the circumferential crack by QC. The key point of the evaluation of these indices is that of the weld joints. The existence of the circumferential welds for the axial crack and the existence of the longitudinal welds for the circumferential cracks could be neglected because the analysis of the structural safety is focused on the probability of the occurance of the severance. Then the quality indices QL and QC consist of the factors shown in Table 1 and Table 2. The quaility indices QL and QC of the mother material part of the straight pipe are assumed to be the unity, and the quality indices QL ($x_1$, $x_2$ , ...., $x_i$ ) and QC ($x_1$ , $x_2$ , ...., $x_i$ ) of the other components are to be constituted to evaluate the quaility relatively.

(It should be noted that the variables $x_1$, $x_2$, ...., $x_6$ in Table 1 and 2 are not independent.)

3.2 "Stress Field Indices"

The load conditions for the analysis of the "damaged conditions" of the model piping system are given as follows.

In the first place, the end displacements (relative displacements) $\Delta x(T)$, $\Delta y(T)$, $\Delta z(T)$ and the end rotations $Rx^{1,2}(T)$, $Ry^{1,2}(T)$, $Rz^{1,2}(T)$ of the model piping system are set in such a way that the maximum value of the resultant moments of the model piping system caused by the thermal expansion at the operating temperature T coincides with that of the cold leg piping of the primary coolant system of 300 MWe class LMFBR shown in Fig.1 under the operating conditions including the up-set condition which should be specified in the design specification. Next, the thermal transient loads and the dynamic loads such as the earthquake which are assumed in the design specification of the real plant are loaded to the model piping system with the same magnitudes and numbers of occurance. Then, the stress analysis of the model piping system is carried out with these load conditions by the procedure usually applied to the design calculation, and the maximum stress intensity $S^i$ of the component i is calculated. Based on the values of $S^i$, the stress fields one of which is effective to drive the axial crack and the other to drive the circumferential crack in the component i is evaluated and normalized by the two stress fields of a certain component of the mother material parts of the straight pipes to generate the stress field index $SL^i$ for the axial crack and the stress field index $SC^i$ for the circumferential crack.

3.3. Selection of the Typical Components

The damage indices $DL^i$ and $DC^i$ of the component i for the axial crack and the circumferential crack respectively is drived in the following manner.

$$DL^i = f\ (QL^i,\ SL^i)$$

$$DC^i = g\ (QC^i,\ SC^i)$$

The components i and j where $DL^i$ is maximum and $DC^j$ is maximum respectively are picked up and these are called the typical components for the axial and circumferential cracks respectively.

It is expected that the typical component for the axial crack should be a certain one of the mother material parts of the elbows such as EM-1 or EM-2 in Fig.4, and that the typical components for the circumferential crack should be one of the weld joints of the nozzle safe-ends such as WC-1 in Fig.4. The following discussion is based on the assumption that the typical components are selected as mentioned above.

3.4 Fracture Mechanics Approach to Fatigue Damage

(1) Analysis of Axial Crack in Typical Component

Assuming that the typical component for the axial crack is EM-1 or EM-2, one should solve the following basic problems to analyze the propatation of the crack by linear elastic fracture mechanics approach:

1) How to evaluate the distributions of the initial defects.

2) How to analyze the three-dimensional propagation of the fatigue cracks.

The fracture mechanics formula to analyze the three dimensional propagation of the fatigue cracks is not in hand. Then the author intends to limit the fracture mechanics approach within the evaluation of crack propagation in the direction of the wall thickness. The corresponding crack length in the axial direction is to be estimated semi-empirically based on the axial distribution of the circumferential stress which is one of the primary fault conditions.

Concerning the evaluation of the initial crack, the surface defect such as the bruise should be considered because the typical component consists of the mother material. One-dimensional fracture mechanics approach requires only the initial depth $a_0$ of the defect, and consequently the linear surface defect in the axial direction is assumed. Above mentioned approach is shown schematically in Fig.5.

The analysis procedure of the "damaged condition" of the typical component for the axial crack could be written as follows.

i) The estimation of the depth $a_0$ of the initial defect.

ii) The analysis of the maximum fatigue crack depth a* at the end of the life time,

$$a^* = a_0 + \sum_i A(\Delta K_i)^B n_i \quad (a^* \leq t)$$

where, A,B; The material constant

$\Delta K_i$; The range of stress intensification factor for the load condition i

$n_i$; The number of the cycles of the load condition i

iii) The analysis of the distribution of the fatigue crack depth in the axial direction;

$$a(x)=f\ (\sigma_\theta\ (x))$$

where, $a(x)$; The distribution of the fatigue crack depth

$\sigma_\theta(x)$; The axial distribution of the circumferential stress (one of the primary fault conditions).

The probabilistic approach to the uncertainties of the primary and secondary fault conditions is applied in the stage ii in the above mentioned procedure. The items to be discussed are as follows.

(i) Appropriateness of the design specification

(ii) Stress Field.

- Triaxiality ⟶ $\Delta K$
- Stress Ratio R ⟶ $\Delta K_{eff}$
- Mode of the loads
- Cyclic frequency
- Accuracy of the stress analysis ⟶ $\Delta K$

(iii) Quality (Other than what is dealt with by the quality indices)

- The effects of the long exposure to the high temperature
- Carburization and decarburization

(iv) Fracture mechanics formula;

- The effects of the liquid sodium environment ⟶ Material Constant A,B
- The effects of the progressive deformation

(v) Inservice inspection;

(vi) Leak detection;

(2) Axial Cracks in Other Components

The "damaged conditions" of the other components for the axial cracks are ranked with the aid of the damage indices $DL^i$ from the analysis of the "damaged condition" of the typical component (EM-1 or EM-2) for the axial crack.

(3) Analysis of Circumferential Crack in Typical Component

It is assumed that the typical component for the circumferential crack is the weld joint WC-1 of the nozzle N-1. The analysis procedure of the damaged condition casued by the circumferential crack in the typical component is similar to the one for the axial crack, but following problems are added to the items to be discussed.

1) Weld defects; The surface weld defects could be dealt with in the estimation of the initial defect $a_0$, and the defects distributed in the weld joint could be dealt with in the evaluation of the material constant A and B of the fracture mechanics formula.

2) In-service inspection; Such a weld joint as WC-1 should be one of the object of the in-service inspection. Feasibility of the in-service inspection should be evaluated.

(4) Circumferential Cracks in Other Components

The "damaged conditions" of the other components for the circumferential cracks are ranked with the aid of the damage indices $DC^i$ from the analysis of the "damaged condition" of the typical component (WC-1) for the circumferential crack.

## 4. Process from "Damaged Condition" to "Severance"

Even if the existence of a long and deep axial or circumferential crack is assumed as the "damaged condition", the probability of the occurance of the severance induced by the ductile unstable fracture should be very low because the internal pressure of the LMFBR primary coolant system piping is low. Then, the process from "damaged condition" to the severance is constituted mainly by the extreme load of low probability of occurance loaded to the "damaged" piping. The examples of such extreme loads are shown in Table 3.

To analyze the degree of the fractures caused by the extreme loads with the evaluation of the probability of the occurance of the extreme load, one could calculated the probability of the occurance of the severance conditioned by the "damaged conditions". With the evaluation of the probability of the occurance of the graded "damaged conditions", the upper bound of the probability of the severance could be evaluated.

## 5. Concluding Remarks

The assumption that the severance of the primary coolant system piping of the loop-type LMFBR should be one of the initiating events of the Design Basis Accident would make the design of the loop-type LMFBR very restricted, and to deny the assumption, the quantitative evaluation of the structural reliability of the piping would play a significant role. But in this preliminary servey, it should be suggested that the design, fabrication, quality assurance and operating experience of the LMFBR piping have not yet fully developed and not well documented, and that it is difficult to catch these scopes in the reliability analysis system. Especially following two points should be noted.

(1) To evaluate the initial defects, the quality indices of the piping, and probability of the occurance of some of the extreme loads, it is inevitable to document the quality assurance program for the design and manufacturing of the LMFBR piping.

(2) To analyze the "damaged conditions", it is important to deal with the history-dependent factors including the environmental effects.

## Reference

[1] GEAP-10207-23, "Reactor Primary Coolant System Rupture Study," Quarterly Progress Report No. 23, P3-3 (Jan. 1971)

Table 1 Quality Index QL against Axial Crack

| Category * | Components | Primary Fault Conditions $x_1$ Chemical Composition | $x_2$ Cold Work | $x_3$ Heat Treatment | $x_4$ Thickness (Surface Condition) | $x_5$ Defect | $x_6$ Strength | Quality Index QL | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| PM | PM-1~10 | I ** | I | I | I | I | I | I | |
| EM | EM-1~8 | I | II | I | II' | I | I | II | |
| WL (Straight Pipe) | WL-1, 5, 6, 7, 10, 13, 16 | II | I | I | II | II | II | III | Shop Welding with Post Weld Heat Treatment |
| WL (Elbow) | WL-3, 4, 8, 11, 14, 15 | II | II | I | III | II | II | IV | Shop Welding with Post Weld Heat Treatment |
| WL (Elbow) and ES | WL-9 (ES-1) WL-12 (ES-2) | II | II | II | IV | III | – | V | |

* cf. Fig.4. ** Roman Numbers indicate the ranking in each column.

Table 2 Quality Index QC against Circumferential Crack

| Category * | Components | Primary Fault Conditions $x_1$ Chemical Composition | $x_2$ Cold Work | $x_3$ Heat Treatment | $x_4$ Thickness (Surface Condition) | $x_5$ Defect | $x_6$ Strength | Quality Index QC | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| PM | PM-1~10 | I ** | I | I | I | I | I | I | |
| EM | EM-1~8 | I | II | I | II | I | I | II | |
| WC I | WC-2, 3, 4, 5, 6, 8, 9, 10, 11 | II | – | II | III | II | II | III | Shop Welding without Post Weld Heat Treatment |
| WC II | WC-1, 7, 12 | II | – | II | IV | III | II' | IV | Site Welding without Post Weld Heat Treatment |
| PS | PS-1, 2, 3 | – | – | – | – | – | – | – | |

* Cf. Fig4 ** Roman Numbers indicate the ranking in each column.

Table 3 Extreme Load Conditions of Damaged Piping System

| Example No | Extreme Loads |
|---|---|
| 1 | Break of one Constant Hanger (CZ-1, or CZ-2), and Design Earthquake |
| 2 | Breaks of two Constant Hangers (CZ-1 and CZ-2) |
| 3 | Reactor Scram and one or two fastened Snubbers |
| 4 | Design Earthquake and Malfunction of one or two Snubbers |

| | Hot Leg | Cold Leg | |
|---|---|---|---|
| | R.V./IHX | IHX/Pump | Pump/RV |
| Material | (304SS) | 304SS | 304SS |
| Diameter (in) | 32 | 32 | 26 |
| Design Condition Temp(℃) P(kg/cm²) | 560/2 | 410/2 | 410/9 |
| O.D.(mm) | 813 | 813 | 660 |
| Thickness (mm) | 11 | 11 | 9.5 |

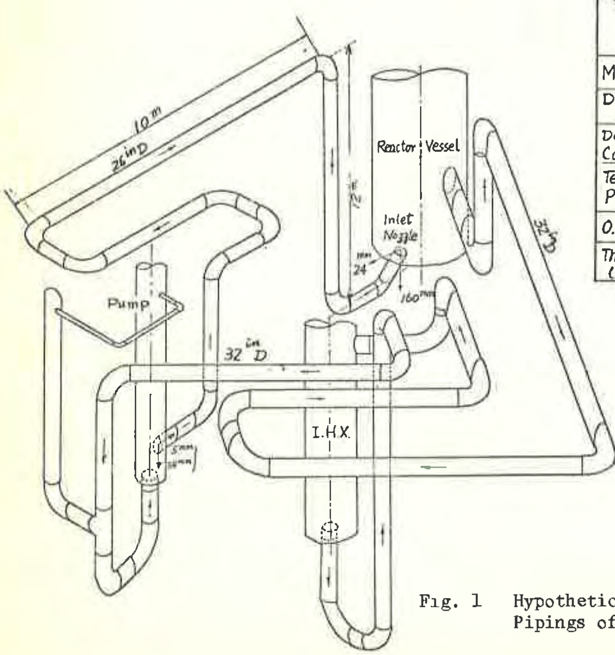


Fig. 1 Hypothetic View of Primary Coolant System Pipings of 300 MWe Class LMFBR

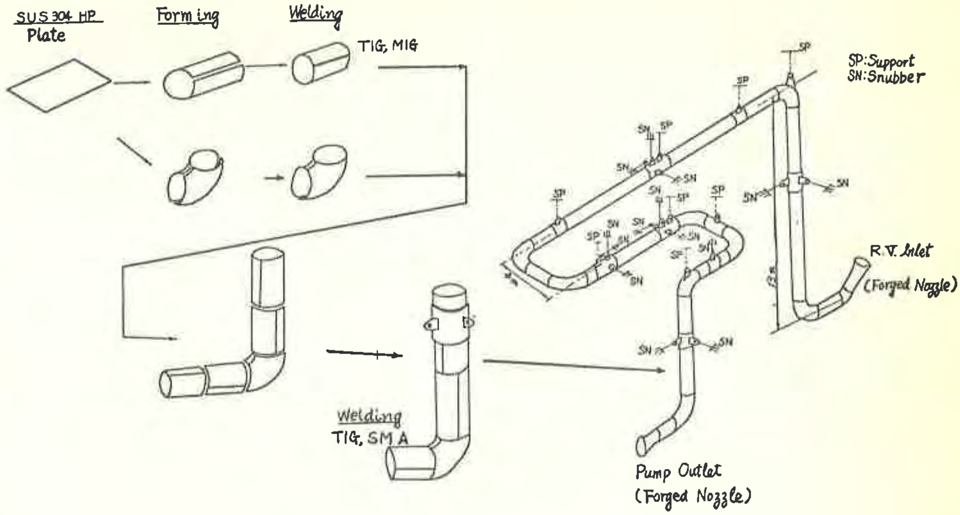


Fig. 2 Hypothetic Fabrication Procedure of Cold-leg Piping shown in Fig. 1

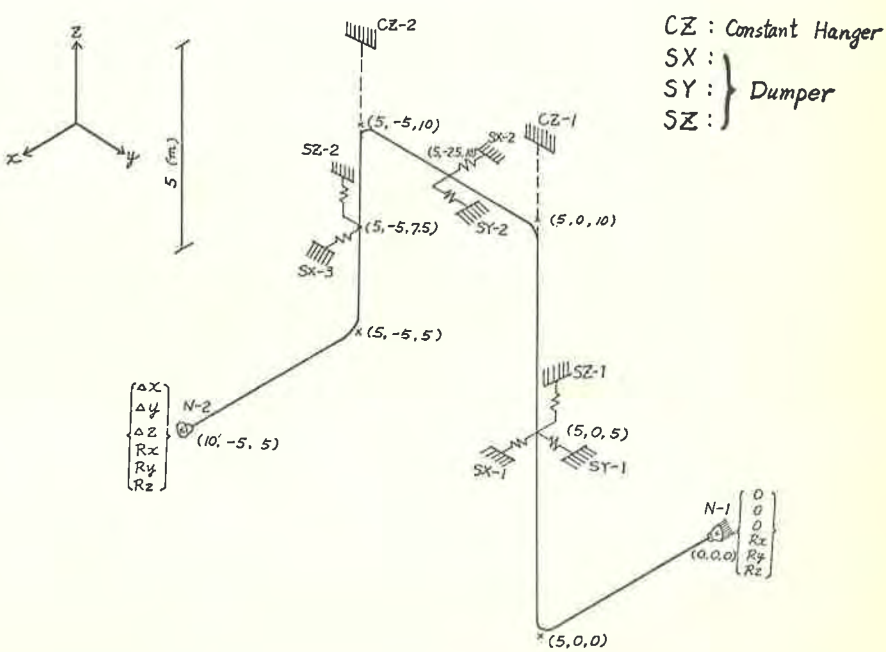


Fig. 3 Model Piping

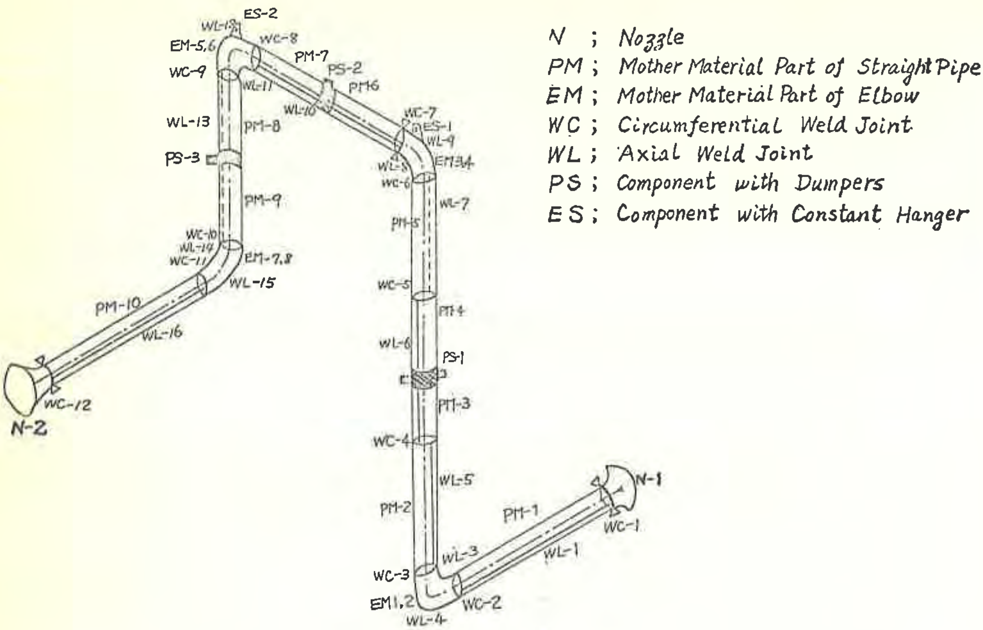


Fig. 4 Structural Components of Model Piping

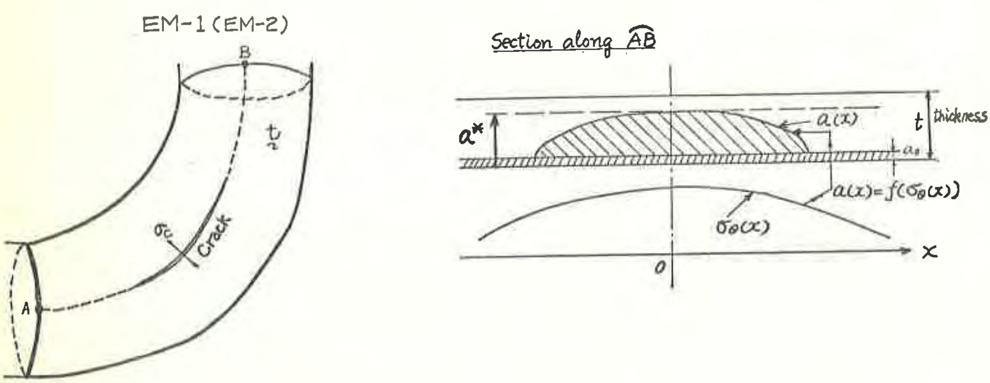


Fig. 5 Propagation of Axial Crack in Mother Material of Elbow