PSA Depending Variable Seismic Allowable Stress

Heki Shibata, Prof.- Dr.

National Research Institute for Earth Science and Disaster Prevention, NIED

ABSTRACT

Recently, the technique and knowledge for the prediction of the ground motions of destructive earthquakes are much improved in the world. Especially, after the accuracy of GPS, Global Positioning System, was improved in May 2000, the prediction has been reached to the level of a forecast in a certain area in Japan. On the other hand, the design basis earthquake and the reference one become higher after Kobe event.

Most familiar term, "allowable stress" has been supported by a concept of safety margin or safety factor. Under a certain number of margin, an expected probability of exceeding the value under a deterministic seismic loading condition can be obtained. Therefore, if the probability of occurrence of a particular load, like the design basis earthquake loading, can be estimated, then the total expected probability of the failure could be estimated. Then, so as to keep the value of the over-all safety margin or the probability of failure constant, the actual allowable stress may be increased according to lowering the probability of occurrence of the reference event. In other words, the seismic allowable stress may be a function of the probability of occurrence of the seismic event at the site area. This idea may be applicable to S_2 design basis earthquake, or the upperbound earthquake, in IAEA or Japanese Seismic Design Guideline and almost corresponding to SSE in U.S.

However, the seismic event is a natural event, and we must expect some uncertainty, therefore, we need a final back-up against unexpected increasing of stress induced by very rare but high ground motions. We may call the higher reference ground motions as, S_3 the severe earthquake for evaluating the over-all seismic safety.

INTRODUCTION

There would be a talk to reevaluate the design basis earthquake for nuclear power plants in Japan in the near future. This came from the destructive capability of strong ground motions as we observed in Hyogoken-Nanbu earthquake-1995, so-called Kobe earthquake. After Kobe event, Japanese Government, the Central Commission for Disaster Prevention, issued the new principle of the seismic design and disaster prevention of structures in general in July 1995. By this, all structures and facilities are required to have two levels of Design Basis Earthquake in general. Before the event, such two level requirement was applied only for nuclear power plants and conventional buildings. The requirement for buildings is the design shall be made in one level earthquake, and then the evaluation of its capacity should be made against a normalized horizontal acceleration 1G (980gal). Afterwards, this normalized 1G value had been re-interpritated as a 1G ground motion input for the level 2 design.

This new re-interpritation seems to be tricky, but it is very effective for preventing catastrophic failures of most of conventional buildings down-town in Kobe. Thus, two level requirement was extended to all fields in general by the Government.

The requirement and the unbelievable effect of the ground motions in the down-town Kobe, so-called Killer pulse to buildings invited the use of such a type of ground motions, which may be induced by a near surface fault within several ten kilometers from a structure, for the design. The technique to simulate such ground motions has been developed very rapidly since Hyogoken-Nanbu earthquake, even there is a doubt, that we can obtain enough data on a movemement of an original fault for the simulation of ground motions.

If we introduce such ground motions for the design, they may include very serious wave-components to fail a structure sometimes. Therefore, the probability of occurrence of such a situation should be carefully examined, because the conditional probability of the failure of structures under this situation may be high. We must examine the occurrence of the event very carefully, and the design criteria of structures, especially seismic allowable stress shall be decided in relation to the probability of occurrence of high level of ground motions, so-called a hazard curve. This paper is discussing this subject based on an idea in relation to an allowable stress system, especially of pipings.

CURRENT RESEARCH PROGRESS AND MODIFICATION OF SEISMIC ALLOWABLE STRESS

It is important to establish a new scope of the system of seismic allowable stress as well as the development of technique for establishing the hazard curve.

The following research projects on seismic failure of piping in nuclear power plants have been running in public domain as follows:

i) Ultimate Strength of Piping System, in NUPEC (Nuclear Power Engineering Corporation).
ii) Behavior of Eroded Piping System, in NUPEC.
iii) Fundamental Behavior of Eroded Piping System, in NIED.

We recognized that the ratcheting behavior of pressurized piping was very significant through the simple torsorial test of 6 in. diameter stainless steel piping, and developed into those of more complicated shape piping [1], and reported it in SMiRT-6 (1981). Since that, the tests have been developed in U.S.A. as well as in Japan. Recently, we are interested in the following two points: the behavior of pressurized piping under high strain seismic loadings, and those of eroded and coroded pipings.

If we consider two or three levels of DBE or seismic loads, we need to set the different levels of allowable stress or limit. The various levels of testings on piping elements and systems have been carried out to fit the multi-level design basis earthquakes, MDBE. Some years ago, there was a discussion, whether or not we could eliminated the concept of OBE in U.S. Approximately 25 years ago, we discussed on the necessity of seismic analysis on the stress in S_1 level for the piping design in Japan. The conclusion was that these should be done. At that time, the allowable stress for S_1 level were in elastic limit, and those for S_2 level were in elasto-plastic level, but the way of computation should be in pseudo-elastic way. Those were based on Section III, ASME PV&P Code primarily, but these were some difference to the operational condition of the previous E.C., or Level C of ASME or Level III of MITI Notification #501 in Japan in details. It took twenty years to establish the details of the system of these allowable stresses approximately, and it finally was published as JEA Guideline, JEAG 4601-1984〔2〕. By the way, this 1984 version of JEAG-4601 is a supplimented to the main body〔3〕 of JEAG 4601, that is, 4601-1987.

Because there was another significant event, the authors have been tried to reconsider the previous approach, that is, the establishment of the concept of "severe accident". And it has been discussing how to revise the "Guideline for Licensing a Nuclear Power Plant against Earthquake〔4〕", which was issued in 1981 and we haven't reached to the conclusion yet. However, the author feels that some concepts of S_S or S_3, which are named as "severe destructive earthquake", may be necessary.

Of course, the concept of S_2 has been employed since the almost beginning of seismic design of nuclear power plants in 1960's. And it was defined the "limit" or "upper bound" earthquake in the 1981 guideline. Immediately after the Kobe event, the adequacy of the guideline was examined〔5〕 by the committee under the Nuclear Safety Commission, and their report said that it was adequate in general, but some results by a simulation on ground motions by the current method exceeded to the design spectrum in some, higher, frequency region.

The method to simulate the ground motions〔6〕 has been very much improved since 1995 as mentioned. Empirical-pseudo Green function method is one of typical one. By using such a technique, the ground motions become more like to the ground motions of Kobe earthquake's one, for example, KOB, so called "Killer Pulse Earthquake". Several commercial computer codes are available now.

The design of equipment and piping systems has been employing the plasto-elastic design, the plant condition C or Ⅲ, even under S_2 earthquake condition against the ground motions obtained by the method designated by the attached explanation to the "Licensing Criteria" issued in 1981. This criteria of allowable stress is based on the pseudo-elastic design as known as ASME section III. However, primarily, the plant condition may be "D" under S_2 earthquake condition. Recently computer programs have been much developed, and non-linear analysis can be made for the business of design levels. Of course, the fundamental behaviors of materials must be known well for each analyses. The reason of recent testings on piping systems is to obtain the knowledge enough to apply such design practice to actual plants.

SAFETY EVALUATION AND HAZARD CURVE OF GROUND MOTIONS, A CONCEPT OF SEVERE EARTHQUAKE

For the modification of the 1981 version of the "Licensing Criteria", an idea of introducing the probabilistic evaluation of nuclear seismic safety of nuclear power plants is discussed. For this we need to establish a seismic hazard curve at site. And then we assume a fragility curve of buildings, equipment and piping systems. It was discussed how to establish the fragility curve of equipment by various researchers including the author, but it is really difficult to establish that of a piping system. The failure mechanism and its probability were discussed on a simple element of piping. The author once tried to simulate the failure process of a piping system in 1986 with Tanimizu. And recent twenty years, various failure tests were done in US and Japan as described in Section 2. Even there are unsolved problems for evaluating the probability of failure of piping systems as discussed later, the failure process seems to be almost clear. We test one specimen on a shaking table for an electric or mechanical component. In this case, by assuming the mean value f_m of its failure as 0.5 of the probability. Then, by assuming also for the shape of its fragility curve and β_u〔7〕 as a Weibull distribution, with its "α" corresponding to "β_u" for PSA could be decided. It was discussed at the OECD/NEA Workshop in Tokyo in 1999. We need to discuss the detailed method how to establish their fragility curve more, not by one point data as in most of cases. However we need to evaluate the mean value of the failure of equipment as well as pipings anyway.

Back to a hazard curve, the author discussed his idea in some occasions. According to the practice in Japan, we consider two levels of Design Basis Earthquakes. Then the third one may be added. This new earthquake motions might be nominated as S_S or S_3 as the author described in previous papers, and the concept is as shown in Fig. 3. There might be more variation, but we don't want to discuss it in details.

The fundamental definition on the magnitude and location is clear and deterministic. However, the earthquake, which has the same magnitude at the same focal point, that is, a particular capable fault may induce different ground motions at different times at the site as Fig. 3. That is, the mean value of the above-mentioned ground motions should be a function of its magnitude and focal distance. However this S_2 may fluctuate, and some upper fluctuated value might be S_S or S_3. Our intention is to evaluate the failure probability against a certain level of such an earthquake or to evaluate its margin, instead of to evaluate it along a hazard curve. The new practice is as follows. To keep this value, that is, the failure probability constant, we must design a piping system by using a variable allowable stress. Of course, we design it against S_2 earthquake by using another allowable stress system which is defined in JEAG4601-1984〔2〕 in Japan as described, and the same type procedure has been using in US. In this circumstance, if we evaluate the fragility curve simply on piping systems, which was designed by a conventional method based on our current criteria, there is a possibility to obtain the scattered failure probability. A new design method and criteria may be brought to us, so as to obtain a uniform failure probability. The control of the failure probability of piping systems against S_S or S_3 as well as that of equipment is significant to get the stable result of the final structure failure, or structured margin (SM) in the sense, which has been used since 1980's SSMRP. This is different from that of SMA in Japan〔8〕. It is significant that some new procedure is to obtain the stable value of the probability of failure against input motions in the sense of over-all probability of failure including that of ground motions. It is necessary to design the system in this sense, that is, the design against S_S or S_3, not only simple probability evaluation. These might be the discussion that it is very awkward to introduce the third design step in general. But the author thinks that it is necessary to avoid a redesign of these systems by the reason of poor result of their seismic probabilistic evaluation based on a hazard curve. Also, if we employ the S-PSA procedure to evaluate the seismic safety of NPP, we need to calculate CDF values at several points on a hazard curve. By using the concept of S_S or S_3, we evaluate the seismic safety at one reference points. We are considering to introduce the evaluation of their seismic safety in parallel to their design procedure (in Fig. 4). This might be helpful to design it to eliminate unnecessary repeating. In the following chapter, these subjects will be discussed. Also, it should be mentioned that the seismic probabilistic assessment of structures and facilities is not necessary to go to CDF as well as SMA, which is only for structural matters. On the other hand, that of a containment is out-of Level 1 PSA, but not much difference to other structures. Actually we need to discuss what situation is a seismic failure of a piping. The author will discuss it in another occasion.

CONCEPT OF PROBABILISTIC BASE SEISMIC ALLOWABLE STRESS AND SEISMIC FAILURE PROBABILITY

Regarding to Seismic PSA, we have not much discussed on the probability of a piping failure induced by the seismic event. A seismic failure of significant piping systems is not related to the core damage directly, but it is very significant to initiate to core damage conditions.

Here we assume that a piping failure would be induced by an earthquake. $p\ (A_i \mid E)$: conditional probability of occurrence of incident i of piping failure induced by an earthquake E, where $p\ (E)$: probability of occurrence of an earthquake E.

Then

$$\mathrm{CDF_p} \propto \sum_i p\left(A_i \mid E\right) p\left(E\right) \qquad (1)$$

should be constant, that is, the core damage frequency caused by piping failures $\mathrm{CDF_p}$ induced by a particular earthquake should be constant as well as possible under the same conditions of other related systems. This is the target of a piping design, discussed here.

Then, we assume that $p\ (A_i \mid E)$ is decided by the relation of the induced seismic stress by the earthquake E to allowable stress. Also, this relation must be developed into the usage factor U_d, design value, and U_a : allowable usage factor for the plant condition VI or D against S_2. The allowable usage factor should be decided by the testings as well as the analytical approach. The damage of piping supports including building parts may add additional reasons of piping failure, but we do not consider it here. Of course, we must consider such a problem as the subject of S-PSA on piping failure.

Our target is to keep the $\mathrm{CDF_p}$ constant under the assumption of other conditions are unchanged, that is, the probability of occurrence of seismic induced piping failure should be constant by taking account of the rate of occurrence of DBE, such as S_2 or S_3. Therefore, if we can assume the probability of occurrence of these DBE for the design or evaluating, the allowable stress or limit of pipings could be higher than before, based on the knowledge obtained by testings as well as those estimated by the assumption and analysis. This concept may be extended into equipment, but it is not discussed here.

PRACTICAL APPROACH TO PROBABILISTIC BASE SEISMIC ALLOWABLE STRESS

A piping system is continuous, and usually we analyze it at evaluation points along the line. For a practical pipe line such as a recirculation system of BWR, we select more than 100 points (in Fig.5), and compute their stresses based on the code. In parallel, we calculate more dense distribution of stress to get the detailed stresses by usind a FEM code in some cases. The highest point of the stress in a system is only one or two usually, and also comes from the stress index near by tees or elbows according to the design code. The value of stress, which is in a primary stress or a secondary stress, is usually different from the actual value obtained by FEM, but we expect that the highest real stress would be induced near by such an area designated by the design code. Therefore, the author considers on the code-based calculated stress in the following discussion.

Based on the previous study [9], which was done approximately twenty years ago, the most of piping failure would be induced by an over-stress of the primary one based on S_y, but we expect its actual failure might be based on the combination of ratcheting and fatigue and some tests proved it. Their behavior can be simulated by a law, so called Asada's law; combined plastic ratcheting and fatigue limit law, like the S-N Fatigue criteria, as described in the reference [1], and this concept has been developed.

As an practical assumption, the usage factor based on this extended S-N curve considering the failure mode above is enough to express the actual failure, almost all elements of piping systems such as elbow, tees and valves. This expanding usage factor approach to degraded piping system may be also possible if we have data on a degraded material in the form of an S-N curve obtained by testing or estimating under a degrading state. NUPEC and NIED have been working for that since 2000 under a guidance of Shiratori, Professor of Yokohama Nat'l. Univ.. Subjects of degrading of piping system are discussed in the view-point of the change of vibration characteristics in previous researches. Actual examples of failures of pipings in the plant are mainly come from thinning by erosion and thermal fatigue mainly, and these phenomena can be expressed by the usage factor on a plasto-elastic base S-N curve.

FRAGILITY CURVE AND USAGE FACTOR

Usually, the fragility curve is drawn as a function of input-acceleration as *P* (*acc.*), but we can define it as a function of the usage factor *P* (*U*). The safety factor or margin in frequency, defined by ASME Section III, is said to be 20, and it does not establish a factor for this combined plasto-elastic law. If we consider the ratcheting effect, the author's group found that the safety factor can be evaluated as 6 ~ 8 as reported some years ago (Fig. 6)[1]. In this case, it is a problem how to select the safety factor, or margin compare to the original concept in ASME.

We have some data, obtained by testings, U_f: the usage factor to reach to 1 means along crack or double-ended brake. There are several stages for the criteria of nominal failure state of pipings.

i) elastic limit: 0.2 % strain → usage factor analysis, if over this limit.
ii) plasto-elastic limit in Plant Condition D/VI: 1 % strain, and
iii) catastrophic limit in Severe Condition: 5% strain.

In the conditions; i) and ii), U_d should be less than 1, and near to 1 in the condition iii). This value should be decided based on the distribution of testing values. It has been not definite, which is practically better either the safety factor should be 20 as the ordinary fatigue or that it should be around 8, as near to the practical case where the ratcheting effect would be not evaluated.

For the Seismic PSA on piping systems, the fragility curve expressed by a usage factor should be employed. It is not exactly known how the uncertainty of the curve would be. According to the author's experience, the geometry of a piping would be changed, for example, its diameter increases 5 ~ 10 %, then many small cracks in lateral would cause for torsional loads, and some of them will become a leading crack by cyclic loads, then it would penetrate and cause penetrated crack and reach to a double-ended rapture within several load cycles.

There is an uncertainty, but the phenomenon is rather stable and we can expect a definite result by the testing. However, in a case of double weak points system like Z shape piping system with two elbows, both critical parts are interfering to another through the distribution of moments, and it is difficult to predict which crack may fail at first. This is not significant as a practice of S-PSA, but as a safety design, for example, where we set an isolation value, we need to decide the weakest point through the system sometimes.

CONSEQUENCE ANALYSIS AND STRUCTURAL ANALYSIS OF PIPING SYSTEMS IN S-PSA

To avoid a vital accident of the total system, it is important to analyze the effect of a failure of a particular part of the piping system to the total safety of the plant. The detailed layout as a system, for example, how to isolate their sections to avoid the large LOCA of the whole system. This has been not discussed well, but, if we employ the higher level allowable stress, we need to consider that the distribution of weaker sections in relation to their calculated stresses, and the safety layout of a piping configuration, especially, layout of valves, especially, check valves might be a significant part of the piping design. And it is necessary to keep the seismic margin uniform as well as possible through the system. For this purpose, we can extent the concept discussed here to a variable allowable stress.

CONCLUDING REMARKS

The last part of this paper, the significance of layout design in relation to the safety of the function of piping systems. To revising the allowable stress or allowable strain of piping system upto plasto-elastic region, we must consider the consequence induced by the revised DBE.

Also it should be mentioned that this evaluation should be done under the assumed conditions, fatigue effect, ratcheting effect and degraded, of life-through, such as 5, 10, 25, 40, and 60 year, for example, even the author does not discuss in details in this paper.

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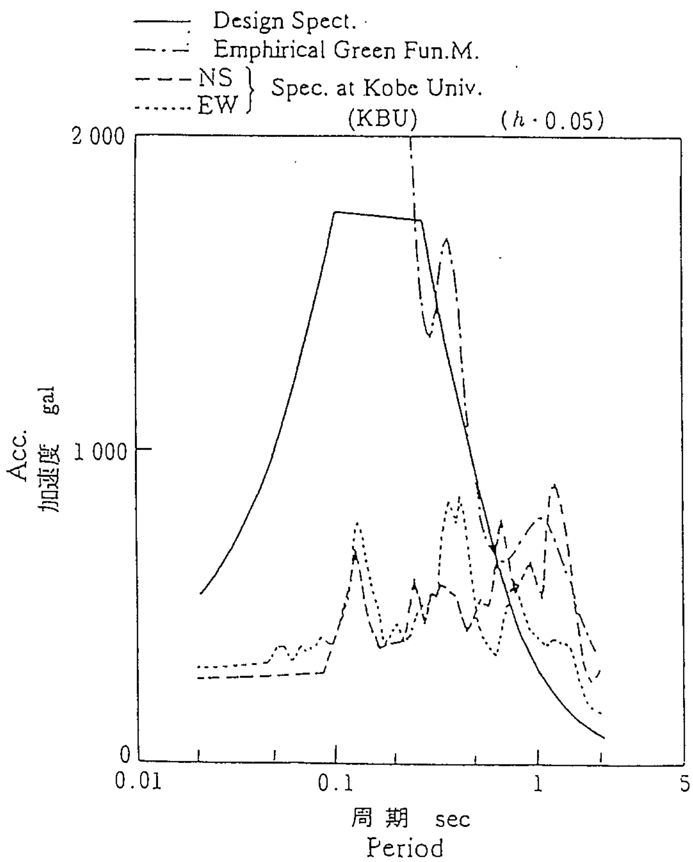

Fig. 1 Comparison of Ohsaki Spectrum to Response Curve at KBU

Sequence of Failures of Office;
Kobe Branch, Nippon Broad Casting Corp., NHK;
Reading out from Video Image

Short Dicsriptions of Images Obtained by Digital Memory Device for 10 second-ahead recording Video

i: small articles (books) on the desk are slightly moving.

↓

a: large motions of articles are observed.

↓

b: overturn of file-cabinet

↓

c: TV set is dropping from a rack.

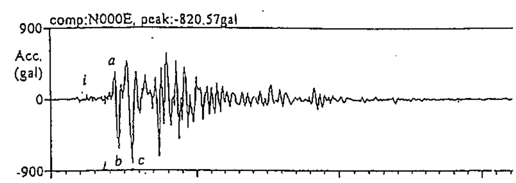

Fig. 2 Ground Motions of Hyogoken-Nanbu earthquake And Significant Moments to Failure of Structures

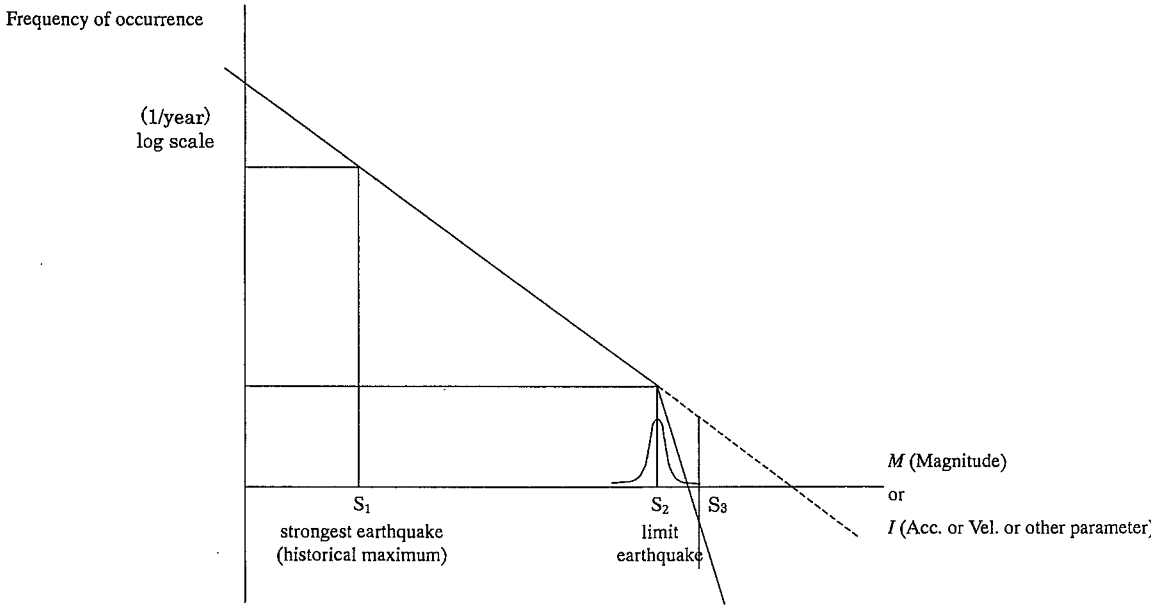

Fig. 3 Concept of Hazard Rate and DBEs

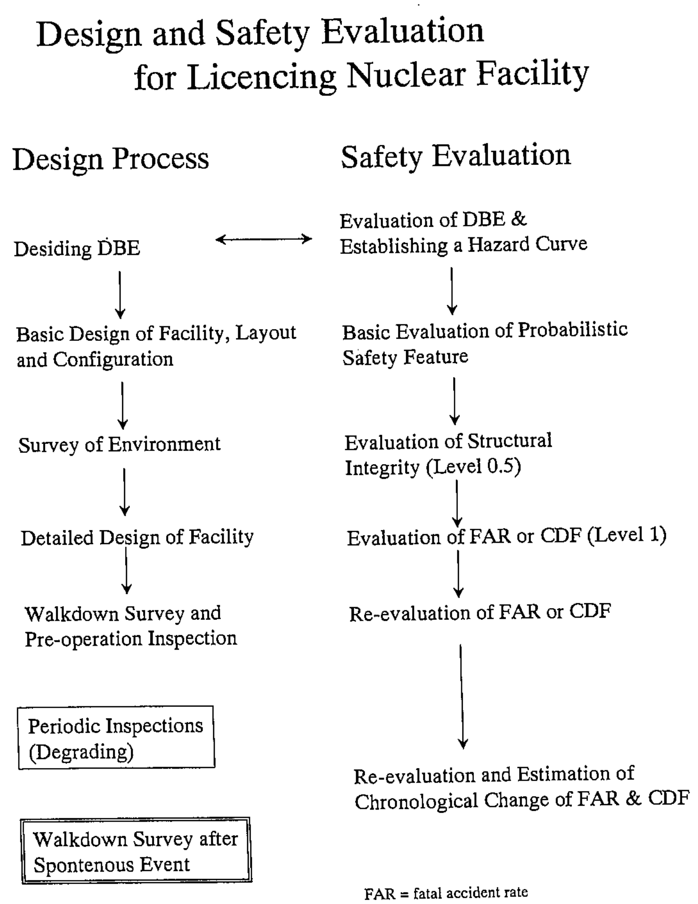

Fig. 4 Flow of Licensing by Design Practice & Safety Evaluation

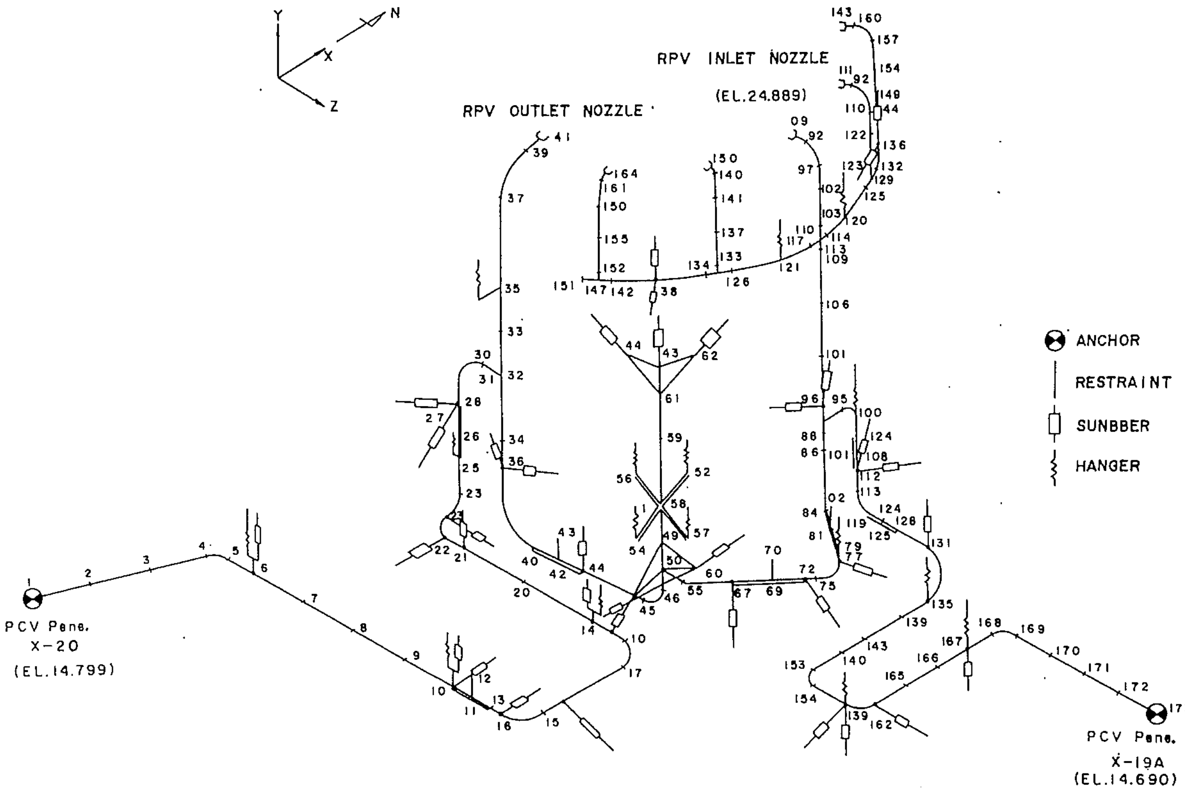

Fig. 5 Example of Complex Piping and Supporting Devices (BWR, PLR-piping)

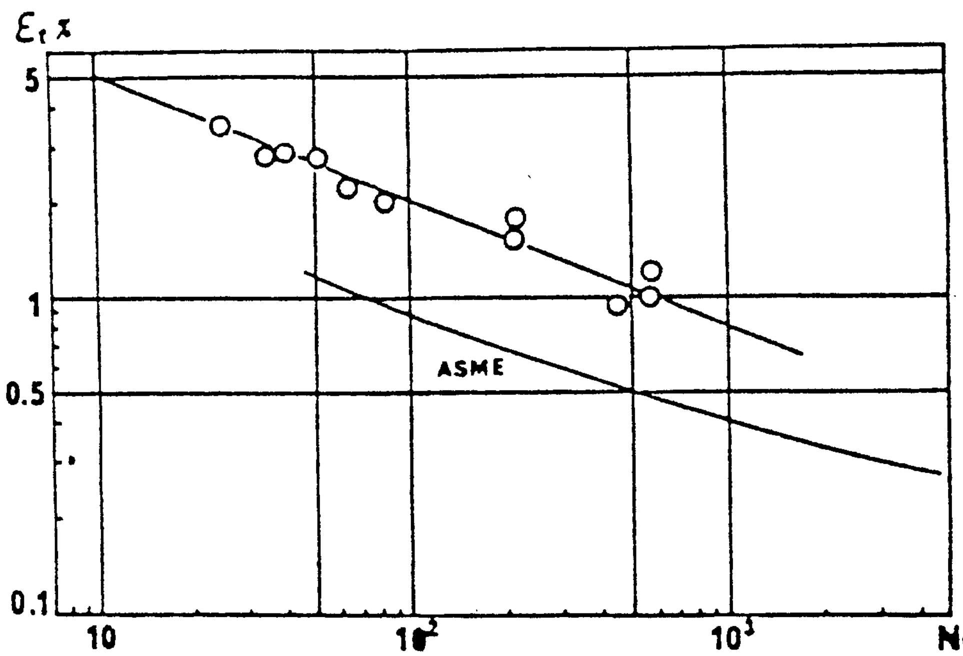

Fig. 6 Ratcheting fatigue life