UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

June 29, 1982

Docket No. 50-237
LS05-82-06-115

Mr. L. DelGeorge
Director of Nuclear Licensing
Commonwealth Edison Company
Post Office Box 767
Chicago, Illinois 60690

Dear Mr. DelGeorge:

SUBJECT: DRAFT SAFETY EVALUATION OF SEP TOPIC III-5.A, HIGH ENERGY PIPE BREAKS INSIDE CONTAINMENT, INCLUDING REQUEST FOR ADDITIONAL INFORMATION FOR THE DRESDEN NUCLEAR POWER STATION UNIT 2

Enclosure 1 is our draft safety evaluation of SEP Topic III-5.A. This assessment compares the methods you have proposed for the mechanistic evaluation of High Energy Pipe Breaks Inside Containment (HEPB) with the criteria and methods used by the regulatory staff for licensing new facilities. As noted in our draft safety evaluation, we have taken positions and required some additional information to finalize our review of your proposed analysis methods and criteria. You are requested to provide, within 30 days of the date of this letter, the necessary information and/or revise your analysis methods to be consistent with the identified staff positions. The 30 day response is necessary to ensure that your analysis, upon completion in September 1982, will be acceptable to the staff and that this topic review is appropriately considered in the integrated assessment. We have also enclosed guidance (Enclosure 2), which is being used to resolve open items on this topic at other SEP facilities. This guidance provides alternative approaches to purely mechanistic (i.e., current Standard Review Plan) evaluations of HEPB.

This evaluation and your committment to evaluate and upgrade, if necessary, your facility for High Energy Pipe Breaks Inside Containment will be a basic input to the integrated assessment for your facility.

The reporting and/or recordkeeping requirements contained in this letter affect fewer than ten respondents; therefore, OMB clearance is not required under P.L. 96-511.

Sincerely,

Dennis M. Crutchfield

Dennis M. Crutchfield, Chief
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Division of Licensing

Enclosures:
As stated

cc w/enclosures:
See next page

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SYSTEMATIC EVALUATION PROGRAM
TOPIC III 5.A
DRESDEN 2 NUCLEAR POWER STATION

TOPIC: III-5.A, Effects of Pipe Break on Structures, Systems and Components Inside Containment

I. INTRODUCTION

The safety objective of Systematic Evaluation Program (SEP) Topic III-5.A, "Effects of Pipe Break on Structures, Systems and Components Inside Containment," is to assure that pipe breaks would not cause the loss of required function of "safety-related" systems, structures and components and to assure that the plant can be safely shut down in the event of such breaks. The required functions of "safety-related" systems are those functions required to mitigate the effects of the pipe break and safely shut down the plant.

II. REVIEW CRITERIA

General Design Criteria 4 (Appendix A to 10 CFR Part 50) requires in part that structures, systems and components important to safety be appropriately protected against dynamic effects, such as pipe whip and discharging fluids, that may result from equipment failures.

The current criteria for review of pipe breaks inside containment are contained in Standard Review Plan 3.6.2, "Determination of Break Locations and Dynamic Effects Associated with the Postulated Rupture of Piping," including its attached Branch Technical Position, Mechanical Engineering Branch 3-1 (BTP MEB 3-1).

III. RELATED SAFETY TOPICS AND INTERFACES

A. This review complements that of SEP Topic VII-3, "Systems Required for Safe Shutdown."

B. The environmental effects of pressure, temperature, humidity and flooding due to postulated pipe breaks are evaluated under SEP Topic III-12, "Environmental Qualification of Safety-Related Equipment."

C. The effects of potential missiles generated by fluid system ruptures and rotating machinery are evaluated under SEP Topic III-4.C, "Internally Generated Missiles."

D. The effects of containment pressurization are evaluated under SEP Topic VI-2.D, "Mass and Energy Release for Possible Pipe Break Inside Containment."

E. The original plant design criteria in the areas of seismic input, analysis and design criteria are evaluated under SEP Topic III-6, "Seismic Design Consideration."

IV. REVIEW GUIDELINES

The licensee's break location criteria and methods of analysis for evaluating postulated breaks in high energy piping systems inside containment have been compared with the currently accepted review criteria as described in Section II above. The review relied upon information submitted by the licensee, Commonwealth Edison Company (CECo), in Reference 1.

V. EVALUATION

A. Background

On July 20, 1978, the SEP Branch sent a letter (Reference 2) to KMC, Inc. requesting an analysis of the effects of postulated pipe breaks on structures, systems and components inside containment for SEP Plants. In that letter, the staff included a position that stated three approaches were appropriate for postulating breaks in high energy piping systems either $P \geq 275$ psig or $T \geq 200°F$. The approaches are:

1. Mechanistic
2. Simplified Mechanistic
3. Effects Oriented

The staff further stated that combinations of the three approaches could be utilized if justified.

On December 7, 1978, the NRC staff sent another letter (Reference 3) to CECo. requesting the licensee to provide some technical information and evaluation of the subject topic for staff to compare the plant design to current criteria and to evaluate the significance of potential differences.

Subsequently, several meetings were held between the staff and the representatives of the licensee and its consultant (EDS Nuclear) to discuss the subject matter. As part of redirection of the NRC Systematic Evaluation Program, the licensee provided the Interim Progress Report on the subject topic on June 4, 1982 (Reference 1).

The objective of Reference 1 is to present the program plan for resolution of SEP Topic III-5.A at Dresden 2 Nuclear Power Station as well as key elements of the technical approach being utilized.

B. Summary of Findings

1. The program plan developed by Commonwealth Edison for resolution of SEP Topic III-5.A at Dresden 2 Nuclear Power Station consists of the following six major tasks:

a. Finalize Program Plan
b. Define Mechanistic Break Locations
c. Develop Target Evaluation Criteria
d. Perform Interaction Evaluation
e. Perform Cost/Benefit Analysis
f. Perform Additional Analysis (as required)
    i. Fracture Mechanics Evaluation
    ii. Rigorous Jet Impingement and Pipe Whip Analysis
    iii. Rigorous Containment and Structure Damage Analysis
    iv. Piping Stress Analysis
    v. Restraint Feasibility Study

At the present time, the first three tasks have been completed and the interaction evaluation is in progress. The anticipated completion date for this study by the licensee is September 1982.

2. Current criteria require that through-wall leakage cracks be postulated in moderate energy line piping (<200°F and <275 psig). The licensee has not addressed this subject in this SEP topic assessment.

3. The licensee has defined high energy fluid systems as those that are maintained under conditions where either or both the maximum operating pressure exceed 200°F and 275 psig respectively. Those piping systems that operate above these limits for only a relatively short portion (less than approximately two percent) of the period of time to perform their intended function, are excluded from evaluation. This is consistent with current criteria.

4. The licensee has utilized the Mechanistic Approach in its evaluation of high energy pipe break inside containment. Based on the information submitted in Reference 1, we have concluded that the criteria used to define the break locations and the break types are in accordance with currently accepted standards.

5. We have reviewed the licensee's information pertaining to pipe whip load formulation. Based on the information currently available, we have determined that the licensee's approach is, in general, acceptable. However, the detailed methodology and specific application of Reference 4 to the licensee's pipe whip load calculation will be reviewed when the results of licensee evaluation become available.

6. The licensee's calculations of jet impingement loads on various targets are based on the methodology presented in ANSI/ANS 58.2-1980. Based on the information submitted in Reference 1, we have concluded that the licensee's methodology including its basic assumptions for calculating the jet impingement loads is acceptable.

7. We have reviewed the information pertaining to the pipe whip and jet impingement interactions with the drywell liner, Reactor Pressure Vessel (RPV) pedestal and biological shield wall. Based on the information submitted in Reference 1, we have determined that the licensee's approach is, in general, acceptable except as follows:

   a. Section 4.2 of Reference 1 references Chicago Bridge & Iron Company (CB&I) Test Report (Reference 5). The CB&I test indicates that when a spherical shell segment having a shell thickness of 0.75 inches is loaded over a large enough area, i.e., equivalent to a 14 inch diameter or larger circle, deformation of the plate over 3 inches can occur without failure of the plate segment. Based on this test result, the licensee concludes that for breaks occuring in piping greater than 14 inches in diameter, even if contact occurred with the drywell liner, the amount of liner deformation, as limited by the concrete shield wall, would not result in a liner failure. Accordingly, no acceptable interactions are considered to result with the drywell as a consequence of breaks postulated in piping greater than 14 inches in diameter. However, it should be noted that the CB&I test was performed under essentially static conditions. It is not clear that the test result is also valid for the dynamic loading which would be experienced as a result of pipe whip. In addition, the particular test applies a concentrated load of 235 tons over an area, equivalent to a 14 inch diameter or larger circle. This assumption may not always be valid because the impact area of a 14 inch diameter or larger pipe may be smaller than the assumed area. Thus, our concern is that in the case of applying concentrated dynamic load over a small area the steel plate may be perforated before the deformation is terminated by the concrete shield wall. Therefore, based on the information submitted, we have determined that the licensee has not provided a sufficient justification to use the CB&I test results in its case.

      The licensee should select a worst case configuration or other alternative to demonstrate that the impact load or energy produced as a result of postulated pipe break for piping greater than 14 inch diameter does not exceed the load or energy required to penetrate the containment liner and wall. In performing this evaluation with static analysis or static test, the dynamic load factor has to be considered. The licensee can take into account the following considerations:

      i. Actual liner thickness with respect to the impact location; and
      ii. The combined crack propagation time and break opening time of the pipe may be long enough to depressurize the system such that the whipping pipe could not produce sufficient energy to penetrate the containment wall.

b. The licensee should provide the technical bases for Figure 4-1 of Reference 1 with respect to the energy absorption capacity of containment liner (based on 80 percent penetration).

c. The licensee should clarify the technical bases for Figure 4-2 of Reference 1 and the use of 2500 psi as an upper bound for jet impingement loading on the drywell liner (page 11, Reference 1).

d. The licensee should provide the detailed methodology including basic assumptions used in arriving at screening criteria for RPV pedestal and biological shield wall, i.e., the allowable pipe whip loads and maximum allowable jet impingement pressure, for postulated pipe break interactions with RPV pedestal and biological shield wall (Figures 4-3 and 4-4, Reference 1).

8. In considering the damage criteria (Section 4.5 of Reference 1), the licensee has used the assumption that a jet or whipping pipe is considered to inflict no damage on other pipes of equal or greater size and equal or greater thickness. It is the staff's position (Reference 7) that the effects of jet impingment should be considered and evaluated regardless of the ratio of impinged and postulated broken pipe sizes.

9. In determining the acceptability of target pipe (Section 4.3.2 of Reference 1), the licensee has used a criterion that the limiting factor for an applied equivalent static load is that the resulting strain in the target pipe material does not exceed 45 percent of the minimum ultimate uniform strain of the material at the appropriate temperature. This criteria is acceptable for avoiding cascading pipe breaks. However, some piping systems are required to deliver certain rated flow and should be designed to retain dimensional stability when stressed to the allowable limits associated with the emergency and faulted conditions, i.e., the functional capability of the piping is required to be demonstrated. The licensee should provide justification to assure that the target piping will remain functional as a result of jet impingement and pipe whip interactions.

10. The licensee's approach for the alternative safety assessment for selected high energy pipe break locations using fracture mechanics analysis is not completely consistent with the staff guidance on the subject as described in Appendix 1 to Attachment to Enclosure 2. For example, the licensee did not address the detectability requirements. The staff recommends that the licensee consider the staff guidance as provided in Enclosure 2 for resolution of unresolved interactions.

VI. CONCLUSIONS

Based on the information submitted by the licensee, we have reviewed the criteria pertaining to the locations, types and effects of postulated pipe breaks in high energy piping systems inside containment. We have concluded that the criteria used to define the break locations, the break types, the jet impingement loads, and the pipe whip analysis are, in general, in accordance with currently accepted standards. We have also determined that it is acceptable under current SEP criteria to use the interaction study to evaluate the effects of postulated pipe breaks to determine the acceptability of plant response to pipe breaks.

However, we have found the scope of program plan, the containment integrity evaluation, the damage criteria for jet impingement, the target pipe analysis criteria, and the fracture mechanics approach as identified in Items B.2, B.7, B.8, B.9, and B.10, respectively, have not been addressed adequately in the licensee's evaluation.

REFERENCES

1. Letter from T.J. Rausch (CECo) to D.M. Crutchfield (NRC), dated June 4, 1982, Attachment 1 - Report, "Dreden 2 Nuclear Power Station SEP Topic III-5.A, High Energy Pipe Break Inside Containment Interim Progress Report," dated May 18, 1982.

2. Letter from D.K. Davis (NRC) to KMC, "Assessment of Postulated Pipe Break Inside Containment for SEP Plants," dated June 20, 1978.

3. Letter from D.L. Ziemann (NRC) to Cordell Reed (CECo), "Pipe Breaks Inside Containment for the Dresden 1 and 2 Facilities," dated December 7, 1978.

4. Enis, R.O., Bernal, D.B., and Burdette, E.G., "A Design Guide for Evaluation of Barriers for Impact from Whipping Pipes." Paper from Second ASCE Conference on Civil Engineering and Nuclear Power, dated September 1980.

5. Thullen, Philip, "Loads on Spherical Shells," Oak Brook Engineering Department, Chicago Bridge & Iron Company, Dated August 1964.

6. "Report of the ASCE Committee on Impactive and Impulsive Loads," Civil Engineering and Nuclear Power, Vol. V., dated September 1980.

7. Letter from D. Ziemann (NRC) to D.L. Peoples, "Evaluation of Pipe Whip Impact and Jet Impingement Effects of Postulated Pipe Breaks for SEP Topic III-5.A and III-5.B," dated January 4, 1980.

Enclosure 2

GUIDANCE FOR RESOLUTION OF OPEN ITEMS FOR
TOPIC III-5.A

I. INTRODUCTION

Criterion No. 4 of the Atomic Energy Commission's General Design Criteria, as listed in Appendix A of 10 CFR Part 50, requires in part that structures, systems and components important to safety be appropriately protected against the dynamic effects, such as pipe whip and jet impingement, of equipment failures. The plant must be designed such that the reactor can be shutdown and maintained in a safe shutdwon condition in the event of a postulated rupture of a piping system containing high energy fluid, up to and including the double-ended rupture of the largest pipe in the reactor coolant systems.

II. BACKGROUND

On July 20, 1978, the Systematic Evaluation Program (SEP) Branch sent a letter to KMC, Inc. (SEP Owners Group) which provided three general approaches that could be used to evaluate the effects of fluid systems breaks inside containment. The three approaches, as described in Reference 1, are:

1) mechanistic approach
2) effects-oriented approach
3) simplified mechanistic approach

A combination of the three approaches was permissible if justified.

III. DISCUSSION

As the topic reviews on pipe break effects continued, the need for additional guidance became clear. Using the methodology adopted by the licensee, approximately four hundred break locations inside containment were identified. Considering the effects of the interactions, the number with potentially adverse consequences were reduced to approximately two hundred. Based on these preliminary results, the staff has determined that supplemental guidance is desirable for resolution of these open items.

A. Selection of Break Locations

Break locations need only be postulated at welds and structural discontinuities (i. e., terminal ends, elbows, branch connections) rather than at any point along the pipe. Break locations previously selected under an effects-oriented review may be eliminated from consideration if they do not constitute a structural discontinuity or a weld.

B. Effects on Plant Shutdown

In assessing the effects of the break on plant safety, the main objectives are:

a. to maintain a coolable core geometry following any postulated break.

b. to maintain the capability of safe plant shutdown (definition of safe shutdown consistent with that of safe shutdown reviews).

c. to maintain containment integrity.

The intent of this review should be to determine if the reactor can be safely shutdown following a high energy line break considering a single active failure occurring after the passive event (pipe failure). This does not infer that systems beyond those necessary to handle the pipe break and the postulated active failure must necessarily remain operable. For instance, if the initiating pipe break is not in the reactor coolant pressure boundary (RCPB) and does not cause a rupture of the RCPB, the review should determine the ability to safely shutdown the reactor. In this case operability of systems needed only to mitigate a loss of coolant accident would not be required.

The following factors should be considered when performing the systems reviews:

(1) components that would limit loss of fluid, i.e., check valves, etc.;

(2) energy contained in the reservoir, i.e., positive displacement pump discharge energy versus stored energy within the reactor coolant pressure boundary or within a steam generator;

(3) redundancy and separation of systems;

(4) consideration of non-safety related systems which are unaffected by the event for cooling;

(5) operator action that could be taken to mitigate the event, considering any needed access to the equipment; and

(6) other defined bases.

C. Resolution of Unacceptable Locations

When the potentially unacceptable locations have been culled down by the above methods, the licensee can use the following methdology for resolution of the remaining locations:

(a) demonstrate why corrective measures such as piping restraints, shields or equipment relocation are not practicable;

(b) perform a fracture mechanics evaluation to show that the pipe of interest will "leak-before-break" and that the leakage will be detected well before a break could occur. Guidance on fracture mechanics evaluation as well as augmented inservice inspection and localized leak detection is provided in the attachment.

IV. SUMMARY

Described above are techniques that may be used by the licensee in the evaluation of the effects of pipe breaks. This guidance is intended to supplement the information previously provided in Reference 1.

The guidance provided for a "leak-before-break" approach for resolution of open items is not to make a determination that the current Regulations are met, but to ascertain the safety implications in a plant that was designed prior to current requirements.

REFERENCE

1. Letter, D. Davis (NRC) to J. McEwen (KMC, Inc.) SUBJECT: Assessment of Postulated Pipe Breaks Inside Containment for SEP plants, dated July 20, 1978.

Attachment to
Enclosure 2

GUIDANCE FOR RESOLUTION OF HIGH ENERGY PIPE BREAK LOCATIONS WHERE REMEDIAL MODIFICATIONS ARE IMPRACTICAL

From the results of reviews conducted to date, the staff has concluded that the relocation of equipment or other modifications to mitigate the consequences of some postulated pipe breaks may be impractical due to physical plant configurations or other considerations. Therefore, the staff has determined that for specific locations where relocation of equipment or other modifications to mitigate consequences of pipe breaks are shown to be impractical, fracture mechanics evaluation of the piping should be performed to determine if unstable ruptures could occur in piping that contained service induced large undetected flaws.

The intent of the guidance provided by the staff is to provide reasonable assurance that the mitigation of pipe breaks are addressed. The approach taken is to provide assessment that condition which could lead to a double ended pipe rupture do not exist thereby making it unecessary for high energy pipe break considerations to mitigate effects of a guillotine rupture. This would be accomplished using a defense in depth approach that is a combination of augmented inservice inspection (ISI), local leak detection and fracture mechanics evaluations. Augmented inservice inspections would be performed with the goal of detecting and limiting any service induced flaws to limits prescribed by the ASME B&PV Code, Section XI, approximately 10% thru wall. Should the flaws go undetected, a local leak detection system would be provided with the requisite sensitivity to identify leakage from a through crack, either longitudinal or circumferential, of a length of twice the wall thickness for minimum flow rates associated with normal (Level A) operating conditions. Fracture mechanics evaluations would be performed to determine that for a circumferential or longitudinal through crack of four wall thickness subjected to maximum ASME design code loads (Level D) that:

(1) substantial crack growth does not occur.

(2) local or general plastic collapse (instability) does not occur.

(3) flow through the crack or the effects of a jet from the crack does not impair safe system shutdown.

To provide assurance that a double ended rupture could not occur by unanticipated loads being applied to a large undetected crack, a fracture mechanics evaluation would be performed to demonstrate that a through crack of a length of four times the wall thickness, 90° total circumferential length, or a larger crack if justified for system service experience would remain stable for local fully plastic large deformation bending conditions. The basis for performance of this more conservative fracture mechanics evaluation to assure a double ended pipe rupture would not occur is as follows:

(1) operating experience has shown that unanticipated and undefined loads in access of design can and do occur in piping systems, i.e., water hammer events have failed piping system supports.

(2) uncertainty in: (a) current analysis methods to accurately predict piping loads analysis and (b) prediction of the energy and frequency content of earthquakes and their effect on piping loads.

(3) SEP criteria for evaluation of structures and system resistance to postulated earthquake loads depend on global structural ductility. This assumption is based on the ability to have load redistributions occur. For unflawed piping, the necessary local ductility is certainly provided. However, for flawed sections of piping the ability to sustain fully plastic behavior without crack instability is required to assure prudently that local ductility is preserved.

The details of the guidance for the combined augmented ISI, leak detection and fracture mechanics evaluations are appended as Appendix 1.

Appendix 1

ALTERNATIVE SAFETY ASSESSMENT FOR SELECTED HIGH ENERGY PIPE BREAK LOCATIONS AT SEP FACILITIES

This assessment is required only if a LWR high energy piping system (i.e., 275 psi or higher; or 200 F or higher, etc.) is being considered. It is only required, if a postulated double ended pipe break would impair safe system shutdown by pipe whip (lacking pipe whip constraints) consequences, or by the consequences of the implied leakage or its jet action. The following guidance is for a safety assessment that may be permitted as an alternative to other system modifications or alterations for locations where the mitigation of the consequences of high energy pipe break (or leakage) have been shown to be impractical.

Guidance for Alternate Safety Assessment

The suggested guidance are as follows:

A. Detectability Requirements

Provide a leak detection system to detect through-cracks of a length of twice the wall thickness for minimum flow rates associated with normal (Level A) ASME B&PV Code operating condition. Both circumferential and longitudinal cracks must be considered for all critical break or leak locations. Methods for estimation of crack opening areas are attached in Appendix 2. Surface roughness of the crack should be considered.

B. Integrity Requirements

(1) Loads for Which Level D is Specified

(a) Show that circumferential or longitudinal through-cracks of four wall thicknesses in length subjected to maximum Level D loading conditions do not exhibit substantial monotonic loading crack growth (e.g., staying below J_{IC} or K_{IC} by plastic zone corrected linear-elastic fracture mechanics methods or a suitable alternative[1]. Also assure that local or general plastic instability does not occur for these loading conditions and crack sizes.

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[1] For 4t flaws that are calculated to be greater than K_{IC} or J_{IC}, consideration will be given to; (1) flaw growth arguments, (2) postulation of small flaws sizes than 4t if justified by leak detection sensitivity.

(b) Under conditions in "B.(1)" show that the flow through the crack and the action of the jet through the crack will not impair safe shutdown of the system.

Acceptable methodology for the estimation of crack opening area for a circumferential through crack in a pipe in tension and bending and for longitudinal cracks subject to internal pressure are attached.

(2) Extreme Conditions to Preclude a Double-Ended Pipe Break

Using elastic-plastic fracture-mechanics or suitable alternative show that circumferential through-cracks will remain stable for local fully plastic large-deformation bending conditions under the following additional conditions:

(a) Fully plastic bending of the cracked section is to be assumed, unless other load limiting local conditions (such as elbow collapse) dictate maximum bending loads, for all critical locations.

(b) Assume all system anchors are effective. To simplify the analysis, supports may conservatively be considered inoperative. If supports are included, consideration should be given to the adequacy of the support to resist large loads.

(c) Other as built displacement limits or constraints may be assumed as especially justified (such as displacement limits of a pipe running through a hole in a sufficiently strong concrete wall or floor, etc.).

(d) Assume a through-crack size of 4t or 90° total circumferential length whichever is greater; or a larger crack only if especially justified.

(e) Assume large deformations means deformations proceeding to as built displacement limits or other especially justified limits.

(3) Material Properties

Conservative material properties should be used in the analyses. Sufficient justification must be provided for the properties, both weldment and base metal, used in the analyses.

C. Subcritical Crack Development

Consideration should be given to the types of subcritical cracks which may be developed at all locations associated with this type of analysis. From prior experience and/or direct analysis it should be shown that:

(1) there is a positive tendency to develop through-wall cracks.

(2) if there is a tendency to develop long surface cracks in addition to through-wall cracks, then it should be further demonstrated that the long surface crack will remain sufficiently shallow.

D. Augmented Inservice Inspection

Piping system locations for which corrective measures are not practicable should be inspected volumetrically in accordance with ASME Code, Section XI for a Class 1 system regardless of actual system classification.

Acknowledgement

Assistance in developing this guidance have been provided by Dr. Paul C. Paris, Del Research Corporation (and Washington University, St. Louis, MO) under subcontract K-8195 in support of technical assistance provided by Idaho National Engineering Laboratory, Idaho Falls, Idaho (FIN A-6456).

ESTIMATION OF STRESS INTENSITY FACTORS AND THE CRACK OPENING AREA OF A CIRCUMFERENTIAL AND A LONGITUDINAL THROUGH-CRACK IN A PIPE

by

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Introduction

Formulas for estimating the crack opening area are developed for a circumferential and a longitudinal through-crack in a pipe subjected to several types of loading. For the circumferential crack, estimation formulas are presented for axial force and bending moment applied to the pipe far from the cracked section and for internal pressure loading. For the longitudinal crack, an estimation formula for the case of internal pressure is presented.

Estimation is based on the method of linear elastic fracture mechanics, which requires the knowledge of the solution of stress intensity factor, K, for each problem. For the internal pressure loading, K-solutions are readily available for both circumferential and longitudinal cracks as functions of a single geometric parameter, $\lambda (= a/\sqrt{Rt})$, relating crack size and pipe geometry. Consequently, the crack opening area formulas are also formulated as functions of this single parameter. For the case of tension and bending of circumferential crack, however, the stress intensity factors are not formulated as functions of a single parameter and no simple formula is readily available. Therefore, in this discussion, a typical value of mean radius to thickness ratio, $R/t = 10$, is specifically selected and formulation is made for this value. Estimation formulas are expected to yield a slight overestimate for $R/t = 10$. For smaller R/t ratios, degree of overestimate would increase. The formulas presented here may be used with a reasonable accuracy when R/t ratio is about 10. Formulas for the crack opening for these cases are not available in simple closed forms, but here moderately long power series approximations based directly on the estimating formulas for K are given.

A Circumferential Through-Crack in Tension and Bending

The K formulas are first developed here based on the results recently obtained by Sanders [1, 2]. As stated above, the K solutions for these loadings are not expressed as functions of a single geometric parameter. Sanders presented approximate formulas for the energy release rate for these loadings, which are readily converted into K formulas. The formulas are, in essence, functions of two geometric parameters for given elastic constants, which may be written in either of the following forms.

$$K = \sigma\sqrt{\pi(R\theta)}\,F(\lambda,\theta)$$

or

$$K = \sigma\sqrt{\pi(R\theta)}\,F(\theta,\frac{R}{t}) \qquad (1)$$

where σ is an applied stress, $2R\theta$ is the total circumferential length of through-crack.

In this discussion, θ and R/t are chosen as geometric parameters and the second form of Eq.(1) is employed for the stress intensity expression. Approximate K formulas and the subsequent estimation formulas for the crack opening areas are developed specifically for R/t = 10, which is considered to be a typical value of interest in the present study. That is, the function $F(\theta)$ in the subsequent discussion represents $F(\theta,10)$.

Let P and M be the axial tensile force and bending moment, respectively, applied to the pipe far from the crack location and let subscripts t and b represent respectively tension and bending. The nominal stresses due to tension and bending are defined by

$$\sigma_t = \frac{P}{2\pi Rt}$$

$$\sigma_b = \frac{M}{\pi R^2 t} \qquad (2)$$

The stress intensity factors are expressed in the following forms.

$$K_t = \sigma_t \sqrt{\pi(R\theta)}\, F_t(\theta)$$

$$K_b = \sigma_b \sqrt{\pi(R\theta)}\, F_b(\theta) \qquad (3)$$

where $F_t(\theta)$ and $F_b(\theta)$ are non-dimensional functions. The numerical values of the functions $F_t(\theta)$ and $F_b(\theta)$ are calculated from Sanders' approximate formulas for R/t = 10, which are tabulated as follows.

($F_t(\theta)$ and $F_b(\theta)$ for R/t = 10)

θ	$F_t(\theta)$	$F_b(\theta)$
0°	1.000	1.000
9	1.039	1.037
18	1.151	1.140
27	1.314	1.278
36	1.505	1.425
45	1.725	1.580
54	1.987	1.747
63	2.305	1.934
72	2.702	2.154
81	3.209	2.406
90	3.872	2.760
99	4.764	3.209
108	6.003	3.827

These values represent slight overestimates of $F_t(\theta)$ and $F_b(\theta)$ [1,2]. The following approximate expressions of the functions $F_t(\theta)$ and $F_b(\theta)$ represent the values of the table with a reasonable accuracy (within a few percent).

$$F_t(\theta) = 1 + 7.5\left(\frac{\theta}{\pi}\right)^{3/2} - 15\left(\frac{\theta}{\pi}\right)^{5/2} + 33\left(\frac{\theta}{\pi}\right)^{7/2}$$

$$F_b(\theta) = 1 + 6.8\left(\frac{\theta}{\pi}\right)^{3/2} - 13.6\left(\frac{\theta}{\pi}\right)^{5/2} + 20\left(\frac{\theta}{\pi}\right)^{7/2} \qquad (4)$$

$(0 < \theta < 100°)$

When the pipe is subjected to axial force and bending moment at the same time, the total stress intensity factor is obtained simply by superposition of these separate factors.

$$K_{total} = K_t + K_b \tag{5}$$

The crack opening areas due to tension and bending, A_t and A_b, may be conveniently expressed in the following form.

$$A_t = \frac{\sigma_t}{E} (\pi R^2)\ I_t(\theta)$$
$$A_b = \frac{\sigma_b}{E} (\pi R^2)\ I_b(\theta) \tag{6}$$

where E is the Young's modulus, and $I_t(\theta)$ and $I_b(\theta)$ are non-dimensional functions.

The crack opening area for the tensile loading, A_t, is obtianed by energy method (Castigliano's theorem) as follows:

$$A_t = \frac{1}{t} \frac{\partial U_t}{\partial \sigma_t} = 2\int_0^{\theta} \frac{\partial}{\partial \sigma_t} \left(\frac{K_t^2}{E}\right) R d\theta \tag{7}$$

since

$$G = \frac{1}{Rt} \frac{\partial U_t}{\partial \theta} = \frac{K_t^2}{E} \tag{8}$$

where U_t is the total strain energy in the cracked pipe. Combining Eqs. (3), (6) and (7), the functions $I_t(\theta)$ is obtained as follows:

$$I_t(\theta) = 4\int_0^{\theta} \theta\{F_t(\theta)\}^2 \, d\theta \tag{9}$$

Substituting $F_t(\theta)$ given by Eq. (4), $I_t(\theta)$ is written as

$$\begin{aligned} I_t(\theta) = 2\theta^2\Big[1 &+ \left(\tfrac{\theta}{\pi}\right)^{3/2}\left\{8.6 - 13.3\left(\tfrac{\theta}{\pi}\right) + 24\left(\tfrac{\theta}{\pi}\right)^2\right\} \\ &+ \left(\tfrac{\theta}{\pi}\right)^3\Big\{22.5 - 75\left(\tfrac{\theta}{\pi}\right) + 205.7\left(\tfrac{\theta}{\pi}\right)^2 \\ &- 247.5\left(\tfrac{\theta}{\pi}\right)^3 + 242\left(\tfrac{\theta}{\pi}\right)^4\Big\}\Big] \end{aligned} \tag{10}$$

$$(0 < \theta < 100°)$$

The crack opening area for bending load, A_b, however, can not be obtained as readily because the "crack absent stress distribution" is not uniform along the crack (direct application of the energy method is difficult). Therefore, A_b or $I_b(\theta)$ will be estimated in the following way.

First, comparison of the crack absent stress distributions for tensile and bending loads, the following bounds are imposed on A_b:

$$A_t(\sigma_t = \sigma_b\cos\theta) < A_b(\sigma_b) < A_t(\sigma_t = \sigma_b)$$

or (11)

$$(\cos\theta)I_t(\theta) < I_b(\theta) < I_t(\theta)$$

Where $A_b(\sigma_b)$ is the crack opening area by bending, and $A_t(\sigma_t = \sigma_b\cos\theta)$ and $A_t(\sigma_b = \sigma_b)$ are the crack opening area due to axial force with tension stress $\sigma_b\cos\theta$ and σ_b, respectively. The first approximation would be to take the average uniform stress between these extremes and

$$A_b(\sigma_b) \simeq A_t(\sigma_b \frac{1 + \cos\theta}{2}) = A_t(\sigma_b(\cos \frac{\theta}{2})^2)$$

or (12)

$$I_b(\theta) = (\cos \frac{\theta}{2})^2 I_t(\theta)$$

Since the function $I_b(\theta)$ given by Eq. (12) may yield underestimated values of the crack opening by bending, the stress intensity factors K_t and K_b are compared in a similar manner. Corresponding to Eq. (11), it is obvious that

$$K_t(\sigma_t = \sigma_b \cos\theta) < K_b(\sigma_b) < K_b(\sigma_t = \sigma_b)$$

or (13)

$$(\cos\theta)F_t(\theta) < F_b(\theta) < F_t(\theta)$$

Averaging the extremes

$$F_b(\theta) = (\cos \frac{\theta}{2})^2 F_t(\theta) \tag{14}$$

Comparison of the numerical values of $F_t(\theta)$ and $F_b(\theta)$, however, shows that Eq. (14) always underestimates $F_b(\theta)$ and that the values of $F_b(\theta)$ lie between the following two bounds

$$(\cos \frac{\theta}{2})^2 F_t(\theta) < F_b(\theta) < \frac{1 + (\cos \frac{\theta}{2})^2}{2} F_t(\theta) \tag{15}$$

Therefore, taking the following expression for $I_b(\theta)$ instead of Eq. (14), the risk of excessive underestimation of the crack opening area caused by bending load may be avoided

$$I_b(\theta) = \frac{1 + (\cos \frac{\theta}{2})^2}{2} I_t(\theta) = \frac{3 + \cos\theta}{4} I_t(\theta) \tag{16}$$

where $I_t(\theta)$ is given by Eq. (10).

The total crack opening area caused by axial tension and bending can be written as

$$\begin{aligned} A_{total} &= A_t + A_b \\ &\simeq \frac{\sigma_t}{E} (\pi R^2) I_t(\theta)\left[1 + \frac{\sigma_b}{\sigma_t}\left(\frac{3 + \cos\theta}{4}\right)\right] \\ \text{or} \quad &\simeq \frac{\sigma_b}{E} (\pi R^2) I_t(\theta)\left[\frac{\sigma_t}{\sigma_b} + \frac{3 + \cos\theta}{4}\right] \end{aligned} \tag{17}$$

The effect of the yielding near the crack tip may be incorporated by the customary method of plastic zone corrections in which θ in these formulas is replaced by θ_{eff}. θ_{eff} is obtained by using

$$\theta_{eff} = \theta + \frac{K_{total}^2}{2\pi R \sigma_Y^2} \tag{18}$$

for plane stress (maximum) plastic corrections. Repeated iterative procedures may be necessary for obtaining θ_{eff}.

Circumferential Through-Crack Subjected to Internal Pressure

For a pipe subjected to internal pressure, p , the membrane stress, σ , in the axial direction is estimated by

$$\sigma = \frac{1}{2}\frac{pR}{t} \tag{19}$$

The stress intensity factor for a circumferential through-crack is normally expressed in the following form.

$$K_p = \sigma\sqrt{\pi a} \cdot F_p(\lambda) \tag{20}$$

where $2a = 2R\theta$ is the total circumferential length of the crack, $F_p(\lambda)$ is nondimensional function of $\lambda = a/\sqrt{Rt}$ and the subscript p represents pressure loading. Contrary to the cases of axial force and bending load, the geometric factor $F_p(\lambda)$ for this case is a function of a single geometric parameter as mentioned earlier.

The following formula empirically represents the curve of $F_p(\lambda)$ presented in Rooke-Cartwright's work [3] . The approximate formula is, for convenience, expressed in a form consistent with the formula for longitudinal crack which will be subsequently discussed. Accuracy of the formula is within a few percent over the range specified.

$$\begin{aligned} F_p(\lambda) &= (1 + 0.3225\lambda^2)^{1/2} && (0 \le \lambda \le 1) \\ &= 0.9 + 0.25\lambda && (1 \le \lambda \le 5) \end{aligned} \tag{21}$$

where $\lambda = a/\sqrt{Rt}$.

The stress intensity factor for a longitudinal through-crack of length 2a is given by

$$K = \sigma\sqrt{\pi a}\cdot F(\lambda) \qquad (26)$$

where again $\lambda = a/\sqrt{Rt}$.

The geometric factor $F(\lambda)$ can be empirically expressed over the range of interest by

$$\begin{aligned} F(\lambda) &= (1 + 1.25\lambda^2)^{1/2} && (0 \leq \lambda \leq 1) \\ &= 0.6 + 0.9\lambda && (1 \leq \lambda \leq 5) \end{aligned} \qquad (27)$$

Eq. (27) provides a good approximation for the shell factor $F(\lambda)$ with accuracy of the order of one percent [3, 4, 5, 6].

The crack opening area, A, can be obtained by the method in the previous discussion.

$$A = \frac{\sigma}{E}(2\pi Rt)\cdot G(\lambda) \qquad (28)$$

where $G(\lambda)$ corresponding to Eq. (27) is given by

$$\begin{aligned} G(\lambda) &= \lambda^2 + 0.625\lambda^4 && (0 \leq \lambda \leq 1) \\ &= 0.14 + 0.36\lambda^2 + 0.72\lambda^3 + 0.405\lambda^4 && (1 \leq \lambda \leq 5) \end{aligned} \qquad (29)$$

Iteration with a plastic zone correction similar to Eq.(24) can be applied to account for the yielding effect near the crack tip.