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For Comment

Potential for Low Fracture Toughness and Lamellar Tearing on PWR Steam Generator and Reactor Coolant Pump Supports

Resolution of Generic Technical Activity A-12

R. P. Snaider, J. M. Hodge, H. A. Levin, J. J. Zudans

Office of Nuclear Reactor Regulation

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ABSTRACT

This report summarizes work performed by the Nuclear Regulatory Commission staff and its contractor, Sandia Laboratories, in the resolution of Generic Technical Activity A-12, "Potential for Low Fracture Toughness and Lamellar Tearing in PWR Steam Generator and Reactor Coolant Pump Supports." The report describes the technical issues, the technical studies performed by Sandia Laboratories, the NRC staff's technical positions based on these studies, and the staff's plan for implementing its technical positions. It also provides recommendations for further work. The complete technical input from Sandia Laboratories is appended to the report.

With regard to the fracture toughness issue, the Sandia work resulted in the classification of the 38 pressurized water reactors evaluated into three groups according to the potential susceptibility of their reactor coolant pump and steam generator supports to low fracture toughness. Based on these results, the staff has concluded that those plants in the group with the highest potential susceptibility (Group I) must be evaluated in more detail, and either the structural integrity of the supports demonstrated or measures to assure their structural integrity must be implemented. The need for further review of plants in Group II will be determined based on the results of the review of Group I plants. The reactor coolant pump and steam generator support materials for Group III plants were determined to possess adequate fracture toughness.

With regard to the lamellar tearing issue, the results of an extensive literature survey by Sandia revealed that, although lamellar tearing is a common occurrence in structural steel construction, virtually no documentation exists describing inservice failures due to lamellar tearing. Nonetheless, additional research is recommended to provide a more definitive and complete evaluation of the importance of lamellar tearing to the structural integrity of nuclear power plant support systems. This research will be sponsored by the NRC as a continuing effort to complete Generic Technical Activity A-12.

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PART I - FRACTURE TOUGHNESS OF SUPPORT MATERIALS

1. INTRODUCTION AND STATEMENT OF PROBLEM

1.1 General Information

During the course of NRC licensing review for two pressurized water reactors (North Anna Units 1 and 2), several questions were raised regarding the potential for low fracture toughness of the steam generator and reactor coolant pump supports. The specific technical concern was the capability of the supports to maintain their structural integrity under accident conditions. Lamellar tearing of the support materials was also of concern and is discussed in Part II of this report. Both issues, and thus Generic Technical Activity A-12, are considered to be generically resolved. Fracture toughness criteria and procedures are presented in Section 4.1, and lamellar tearing is discussed in Section 6.

The fracture toughness of a material is a measure of its capability to absorb energy without failure or damage. Generally, a material is considered "tough" when, under stated conditions of stress and temperature, the material can withstand loading to its design limit in the presence of flaws. Toughness also implies that under specified conditions the material has the capability to arrest the growth of a flaw.

The staff's concern in the North Anna licensing process, which led to this generic investigation, was that not enough attention might have been paid to the selection of materials for, and fabrication of, the steam generator and reactor coolant pump supports. A lack of adequate toughness (accompanied by the combination of low operating temperature, presence of flaws, and nonredundancy of critical support members) could result in failure of the support structure under postulated accident (especially loss-of-coolant accident and earthquake) conditions.

To address fracture toughness concerns at the North Anna facility, the licensee undertook tests not originally specified and not included in the relevant ASTM (American Society for the Testing of Materials) specifications on those heats of steel for which excess material was available. The toughness of the A 36 steel was found to be adequate, but the toughness of the A 572 steel was determined to be relatively poor at an operating temperature of 80°F. In this case, the licensee (Virginia Electric and Power Company) agreed to raise the temperature of the ASTM A 572 beams (by auxiliary electrical heat) in the steam generator supports to a minimum of 225°F any time the reactor coolant system is pressurized above 1000 psig throughout the life of the plant. The NRC staff found this to be an acceptable approach to resolve the North Anna concern.

Because similar materials and designs were used in other plants and because similar problems were therefore possible, the review of this matter was incorporated into the NRC Program for Resolution of Generic Issues as Generic Technical Activity A-12, "Potential for Low Fracture Toughness and Lamellar

Tearing on PWR Steam Generator and Reactor Coolant Pump Supports." A copy of the latest revision to the Task Action Plan is attached as Appendix A.

We have determined that 21 plants (referred to later as Group I) do have materials of questionable fracture toughness. Although the questions warrant further investigation, continued PWR operation and licensing are justified in this report while continuing review is in progress.

With the exception of those plants that used ultra-high-strength steels such as maraging grades 300 or 350, which have a high susceptibility to stress corrosion cracking (and consequent danger of brittle fracture from such cracks), the predominant reason for requiring further review of these 21 plants was the use of various steels as follows:

A 515 or A 285	--	Plates or structural shapes
A 53, A 105, or A 106	--	Tubular sections
A 27	--	Castings
A 307	--	Nuts or bolts

The above steels are plain carbon steels for which fracture toughness tests, such as impact or nil ductility temperature (NDT) tests, are not required by the specifications. Furthermore, the specifications permit the production of these steels as semi-killed or silicon-killed, inherently coarse-grained steels. Their use is also permitted in the non-heat-treated condition, so that the product, in the as-furnished condition, can be coarse-grained and of low fracture toughness. In addition, the specified compositions are characteristically relatively high in carbon content, with relatively low manganese-carbon ratios. This combination of factors can be unfavorable to fracture toughness.

An expanded discussion of toughness and the detailed procedure for continuing review are included in Sections 2 and 4.

Task Action Plan A-12 had, as an integral part, the collection of information from all licensees of operating reactors and selected new facility license applicants. Requests for information were sent to licensees in late 1977. Responses to these requests were received during 1978. A listing of the information requested is attached as Appendix B.

The Part I sections that follow present the review of the fracture toughness issue in more detail. Section 2 deals with the method of fracture toughness determination, and Section 3 presents the conclusions of review and assigns the plants to groups based on the potential susceptibility to brittle failure. Section 4 provides the staff's implementation plan and procedure for further review.

1.2 Approach to Fracture Toughness Review

Sandia Laboratories of Albuquerque, New Mexico, was contracted to assist the staff in the review of the information obtained from licensees and applicants. The initial effort included:

1. Categorization of the support designs and materials (as far as practical) and selection of typical designs for further study;

2. A literature search for fracture toughness and lamellar tearing data on the materials in question; and

3. Evaluation of typical designs and selection of those materials which may have low fracture toughness or a potential for lamellar tearing.

With the exception of lamellar tearing, which is discussed in Part II of this report, items 1, 2, and 3 above have been completed. The recognized limitations of the Sandia and staff reviews are noted in Section 1.3 that follows.

The Sandia report discussing in detail the review effort and conclusions is attached to this document as Appendix C. The staff has incorporated the Sandia conclusions into its implementation program (see Sections 3 and 4 of this report). In addition, the Sandia report will be used in formulating new review procedures for plants to be assessed in the future. These procedures will be in the form of revised Standard Review Plans or Branch Technical Positions.

1.3 Limitations of Fracture Toughness Review and Recommendations for Further Work

Because the original licensing action (North Anna Units 1 and 2) involved only the steam generator and reactor coolant pump supports of pressurized water reactors (PWRs), the staff's efforts were directed toward these supports. However, the staff has kept in mind the possibility of expanding its review to include other support structures, such as boiling water reactor (BWR) vessel supports, BWR pump supports, pressurized water reactor (PWR) vessel supports, and PWR pressurizer supports. This expanded review will be undertaken for operating reactors, as appropriate, by NRC's Division of Operating Reactors (Office of Nuclear Reactor Regulation, NRR) and factored into the licensing review for reactors not yet licensed by the Division of Systems Safety (NRR). Meanwhile, continued plant operation and licensing are justified as noted in Section 3 and Appendix A of this report. Furthermore, the information gathered from the study documented herein and the implementation of its results can be applied to other support structures and configurations.

As noted in Appendix C, support joints embedded in concrete were not considered in the generic study. The staff's decision to so limit the review was based primarily on the facts that the integrity of support embedments was not questioned during the original North Anna licensing action and that emphasis should be placed on resolving the most immediate generic issue - whether or not problems similar to those uncovered at North Anna exist at other facilities. Furthermore, it was the staff's judgment that an evaluation of support embedments would require a detailed plant-specific review that was beyond the scope of any segment of the overall generic review.

Concrete anchors/embe : fall into two basic categories: vendor supplied expansion anchors (s. and wedge) and engineered embedments that are fabricated from structural shapes. It is the staff's judgment that review of the design practices associated with either anchoring method would entail a broad and somewhat unrelated study, even : uld such a study be deemed necessary. The subject of pipe support base pl e designs using concrete expansion anchor bolts has been addressed generically by NRC Office of Inspection and Enforcement (IE) Bulletin 79-02 dated March 8, 1979. The IE Bulletin addressed a deficient design practice, which in some cases has led to overloading of anchor bolts. This activity has not uncovered any material property deficiencies associated with either the concrete or steel elements.

The engineered embedments could potentially be subject to the same low fracture toughness problems as other regions of the support structure. However, since similar materials are used in both the embedded and nonembedded sections, any conclusions reached in the generic study would probably be applicable. These questions will be resolved during the implementation phase of Task A-12.

2. METHODS OF FRACTURE TOUGHNESS DETERMINATION

2.1 Selection and Application of Parameter of Interest and Discussion of Review Procedure

A major portion of the Sandia generic review was devoted to the assessment of fracture toughness properties for the materials reported by licensees and license applicants to be used in steam generator and reactor coolant pump supports. The determination of such properties was difficult mainly because of a lack of plant-specific materials testing data. The task was made more difficult by the variability of fracture toughness properties from heat to heat of produced steel. Such variability is directly related to steel mill melting practice, amounts and types of additives, and other mill practices. Welds also demonstrate toughness variability resulting from differences in weld wires, heat input, and welding methods.

To assess the toughness properties in spite of the difficulties noted above, it was decided to first classify the materials of construction into groups. This classification was based mainly upon nil ductility temperature (NDT) considerations and the comparison of NDT with an assumed 75°F minimum operating temperature. Although Table 4.2 of Appendix C shows that several plants have lower operating temperatures, the staff chose 75°F as a "baseline" value because (1) although not the average, it represents a realistic temperature against which properties comparisons could be made; (2) choice of the lowest reported operating temperature (50°F at Arkansas Nuclear 1, Unit 1) as the comparison value could prove to be unnecessarily restrictive for those many plants that exceed the selected value; and (3) the staff will apply conservative factors to determine the acceptable support temperature values to assure adequate toughness. Following sections of this report contain more detail on this determination.

The nil ductility temperature was chosen as the parameter for comparison because of its predominant availability in the literature (where test results are given in terms of this parameter) and also because of its applicability as a basis for the assurance of an adequate level of fracture toughness. At the NDT, the fracture toughness is relatively low and crack propagation from large cracks will not be arrested. As temperature increases above the NDT, the fracture toughness increases very rapidly. Therefore, at temperatures above NDT, rapid crack propagation from relatively large cracks, such as those resulting from the growth of small cracks in locally embrittled regions, will be arrested. This is true even at stresses as high as the yield strength of the material.

A breakdown of the materials into groups based upon NDT as the main parameter, but also considering Charpy V-notch (CVN) data and knowledge of embrittling phenomena, can be found in Table 4.6 of Appendix C. These parameters are all discussed in more detail in Section 2.2 that follows.

The plants were then classified according to their materials of construction. The resulting preliminary ranking is shown in Table 4.7 of Appendix C.

Each plant determined to have materials of questionable toughness from the preceding classification efforts was then given in-depth consideration as delineated in Section 4.7 of Appendix C. Basically, this in-depth review included assessment of the suspect materials at the locations and applications in which they were used. The conclusion of this review is presented in Section 3 of this report.

2.2 Determination of Acceptable Operating Temperatures Based on NDT/ Additional Considerations Regarding Fracture Toughness

The review of the fracture toughness properties of the materials of construction, as expanded upon in Section 4 of Appendix C, included listing and categorizing the materials by grade, product form, and fracture toughness. As noted above, the fracture toughness categorization was partially based on fracture toughness test results in terms of the Charpy V-notch test. Such results were reported only in very few cases, but CVN deserves more discussion because of its application both to the resolution of the fracture toughness issue on supports of future plants and because CVN testing may be required on some materials as part of the resolution of the A-12 task implementation.

Briefly, the CVN test is a means of destructively determining the energy absorption capability of small samples of steel. The results of the test can be used to determine fracture toughness. When fracture toughness testing, usually in terms of CVN values, is specified as a purchase requirement, and compliance with this requirement is reported, such compliance furnishes assurance of an adequate level of material fracture toughness. It also indicates that attention had been paid to toughness requirements in material selection and purchase.

When CVN data were not available, as was generally the case in the A-12 study, categorization was based on NDT values resulting from a comprehensive literature survey. The results of this survey were analyzed statistically so that mean and standard deviation values were established for the material grades used in the supports. Thus, the NDT values of the Sandia report are given in terms of a mean NDT plus 1.3 or 2 standard deviations. These correspond to confidence ratings of about 90 or 95 percent, respectively, that the NDT for any heat of steel in a given group will be below the temperature at 1.3 or 2 standard deviations. (The Sandia report erroneously states "above this temperature.") The criterion utilized in Appendix C for the categorization of the steels was the mean NDT plus 2 standard deviations. This is very conservative, and the staff has determined that, in its implementation review, the "target" acceptable operating temperature should be mean NDT plus 1.3 standard deviations plus a temperature adjustment, as discussed below. The importance of this determination rests in the fact that the actual support minimum operating temperature could determine whether or not the support material toughness is adequate.

Appendix C suggests that, for protection against large cracks in thicker materials, the support operating temperature should be 60°F to 120°F above the highest measured NDT. Because of the general lack of such measurements, we have assumed the highest NDT corresponds to the 1.3 or 2 standard deviations from the mean. The assignment of a higher temperature "target" would depend on the thickness or section size of the material. Because small section sizes are used predominantly in the steam generator and reactor coolant pump supports, the NRC believes that a temperature margin smaller than the suggested 60°F to 120°F is justified. This is reflected in our choice of the criterion mean NDT plus 1.3 standard deviations plus 30°F to 60°F (depending on section size) as noted on Figure 1.

Results of fracture mechanics testing on some grades of steel are also included in Appendix C. These results, in terms of a limiting stress intensity value for plane strain fracture (K_{IC}), would permit a quantitative evaluation of the susceptibility to brittle fracture in terms of limiting stresses and defect sizes. However, little data were available, and these results could only be applied on, in Sandia's words, "a pessimistic worst case basis."

In addition to the above considerations of fracture toughness, the possible occurrence of further embrittling phenomena was included. These phenomena include strain age embrittlement, temper embrittlement, and embrittlement during heat treatment to relieve stresses from carbide precipitation. Such embrittling behaviors can cause large increases in NDT and therefore result in lower fracture toughness. This susceptibility to embrittling phenomena was taken into account in the classification of the materials into groups (see Section 4 of Appendix C).

3. CONCLUSIONS OF REVIEW

After evaluation of the component supports and especially the materials of construction, the plants were classified into groups based on susceptibility to low fracture toughness (and therefore to brittle failure), from higher (Group I) to lower (Group III) susceptibility. These assigned groupings of "susceptibility" to low fracture toughness imply only a relative, not an absolute, ranking. Many factors (initiating event, low fracture toughness in a critical support member in tension, low operating temperature, large flaw) must be simultaneously present for failure of the support system to ensue. The generic evaluation has not uncovered any data that would suggest that initial arguments supporting continued operation (see Appendix A) are in fact invalid. Therefore, the staff has decided that shutdown or restricted operation of operating reactors during the implementation phase is not warranted. Also, we have determined that licensing of pressurized water reactors should continue during the implementation and application of lessons learned from the review. If, however, information is discovered during the course of the staff's plant-specific reviews that would require immediate action, the staff will take such action as appropriate.

The staff has estimated that its implementation review will require approximately two years. Our conclusions regarding continued operation and licensing during implementation are not affected by the estimated length of time required for this work. This is based mainly on the fact that the combination of events required to cause failure is highly unlikely (as discussed in the preceding paragraph), and also includes the knowledge that many plants were classified as Group I only because of a lack of certain information (see Section 4.7 of Appendix C). Receipt of such information could result in the plants being moved to a lower susceptibility group after very little additional analysis.

The staff has concurred in Sandia's final ranking of plants. The three groups of plants, ranked from higher (Group I) to lower (Group III) potential susceptibility to low fracture toughness and therefore brittle failure, are as follows:

GROUP I

Crystal River Unit 3
Davis-Besse Unit 1
J. M. Farley Units 1 and 2
Fort Calhoun
Indian Point Units 2 and 3
Kewaunee
Maine Yankee
Millstone Unit 2
Palisades
Point Beach Units 1 and 2
Prairie Island Units 1 and 2
Rancho Seco
Saint Lucie Unit 1
Surry Units 1 and 2
Three Mile Island Unit 1
Yankee Rowe

GROUP II

Arkansas Nuclear One Unit No. 1
Beaver Valley Unit No. 1
Calvert Cliffs Units 1 and 2
Ginna
Haddam Neck
Oconee Units 1, 2, and 3
H. B. Robinson Unit 2
Trojan

GROUP III

D.C. Cook Units 1 and 2 | Zion Units 1 and 2
Salem Units 1 and 2

The plants listed in Group I will require additional study to ascertain the fracture toughness of several steam generator and reactor coolant pump support materials. As noted above, some of these plants could be reclassified into lower susceptibility groups on the basis of information or simple analysis provided by the applicant or licensee. For example, certain plants were placed in Group I only because of the presence of high yield strength materials that may be subject to stress corrosion cracking. Because information concerning the inservice conditions to which these materials are subjected was not readily available to the staff, the matter was identified for further review.

Other plants in Group I may qualify for reclassification based on the section sizes and restraint conditions in which the questionable materials are used. For example several of the materials, when used in small section sizes, are more resistant to plane strain brittle failure.

The staff has determined that no action on Group II plants should be undertaken pending the results of the review of Group I plants. The bases for this determination are (1) the greater likelihood of adequate fracture toughness in the materials of Group II plants (see Appendix C), and (2) information presented above concerning the combination of factors required for support failure.

Section 4 of this report discusses the planned method of review for plants in Groups I and II.

Group III plants will not be required to take any further action regarding fracture toughness because their materials, design, and construction are considered adequate. (See Appendix C for details.)

The fracture toughness criteria and procedures of Section 4.1, below, together with the discussion of lamellar tearing in Section 6, provide the generic resolution of Generic Technical Activity A-12.

The detailed plant-specific review, categorization, implementation and completion of any follow-on actions deemed necessary will provide assurance that the steam generator and reactor coolant pump support materials of the PWRs included in the review have adequate fracture toughness. Other PWR supports and the supports used in boiling water reactors will be included later in an expanded review as noted in Section 1.3 of this report. We have found no technical basis that would exclude these other supports from such review.

To assure that future plants will benefit from the results of the A-12 effort during their licensing review, the NRC staff will incorporate fracture toughness testing and documentation requirements in the applicable Standard Review Plan. Such requirements had never previously been included.

4. IMPLEMENTATION PLAN AND PLANT-SPECIFIC REVIEW PROCEDURE

The NRC's plan for the implementation of generic results of the fracture toughness portion of Task A-12 is as follows:

1. The staff will study the Group I plants in detail upon receipt of additional information from licensees and applicants as delineated in Appendix D. The review will then proceed in accordance with the plan shown in Figure 1 and will include the materials of embedded supports. Subsequent information will be requested from licensees and applicants as necessary to assure the staff of adequate fracture toughness.

   The staff intends to pursue this issue promptly with Group I licensees. This effort could result in modifications, such as the ancillary heating at North Anna, being required for Group I plants on which adequate fracture toughness cannot otherwise be assured.

2. The staff will request plant-specific information (similar to that described in Appendix B but modified by generic study results) from the following plants that were not reviewed during the generic study, and will review those plants concurrently with those of Group I:

   Arkansas Nuclear One, Unit 2
   San Onofre Unit 1
   Three Mile Island Unit 2*
   Turkey Point Units 3 and 4
   All PWRs undergoing licensing review for which the design of supports has been completed (others will receive guidance from the Standard Review Plan revision)

3. The staff will review Group II plants when the review of Group I plants is well under way. The basis was presented in Section 3 of this report.

4.1 Plant-Specific Review Procedure

Figure 1 shows the plan for the review of the materials of Group I plants. The following discussion elaborates on the more important aspects of the staff's implementation plan.

Keeping the possibility of low fracture toughness in mind, the first step of the plant-specific implementation phase will be to establish the location of the questionable materials in the support structures. At these locations, the factors affecting the susceptibility to brittle fracture will be considered in detail. These factors include the tensile stress level, under both normal and

*The schedule for review of this plant will be determined at a later date.

accident conditions (including LOCA and earthquakes), the temperature of the material, stress concentration areas due to geometric effects, and the proximity of the location to probable sources of defects such as weld cracks. Section size is also a consideration because the susceptibility to plane strain fracture increases with increasing thickness or section size. Section sizes under one inch have a relatively low susceptibility to brittle failure, both because of a generally higher level of fracture toughness and, at these relatively low strength levels, a greatly increased probability of general yielding rather than brittle fracture.

If these considerations indicate that the questionable materials are present at locations that could fail [because of high tensile stresses (both design and residual), lack of redundancy, large section size, or any combination of these and other factors] if the structure is challenged, further consideration will be given to additional factors affecting material toughness. Note again that for failure to ensue, not only must there be a challenge (large load) and low toughness material with no redundant members, but also a flaw of critical size must be present and the operating temperature must be lower than that at which adequate toughness is assured.

The additional toughness factors mentioned above may be obtained from test records from the mill in which a particular heat of steel was formed. These records, in their optimum form, would contain information concerning the steel's composition and tensile properties, the heat treatment and deoxidation practice used in the production of the particular heat, and the rolling practice in use. Although such data will not usually furnish quantitative fracture toughness information, the resulting information, particularly with regard to chemical composition, deoxidation practice and heat treatment, will be very useful in assessing the energy-absorbing capability (fracture toughness) of the steel.

If, however, the review of the available mill data still does not provide assurance of adequate toughness, the staff will then assess any preservice and inservice inspection records for the supports. If such inspections were not performed or if the records are not satisfactory, the staff may require the collection of samples of questionable support materials.

Preservice or inservice inspection, if properly performed, could provide significant information regarding the presence (or absence) of a flaw or flaws large enough to result in brittle failure under load, assuming the support member lacks adequate toughness to resist failure. Such flaws would be assumed to have been induced during fabrication since normal operating loads are small.

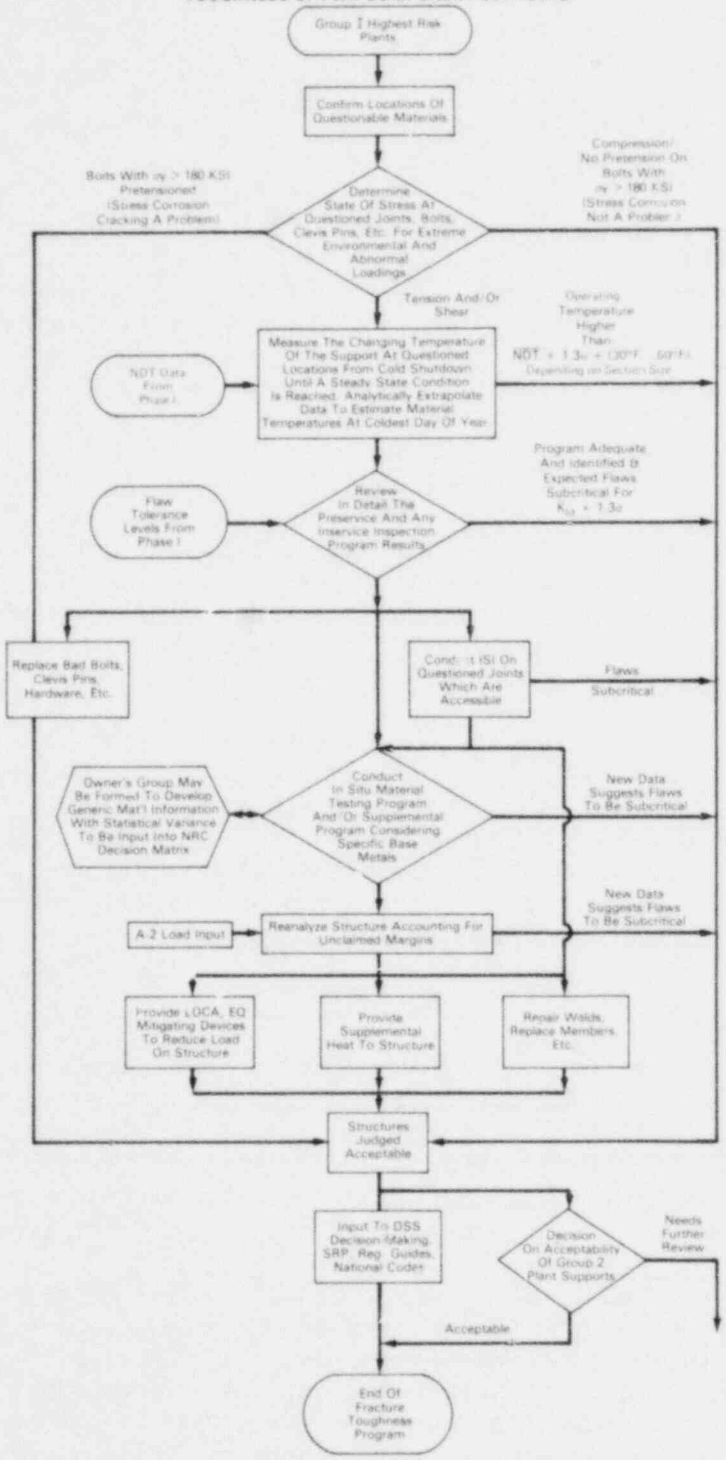
There is presently no requirement, in either NRC regulations or the applicable American Society of Mechanical Engineers Code, for the inservice inspection of steam generator and reactor coolant pump supports other than the visual inspection of reactor coolant pump supports once every 10 years. The lack of accessibility to critical locations (questionable materials, large accident tensile loads) may become a large factor in determining the efficacy and value of such inspections. The staff will use non-destructive examination (NDE) expertise in its implementation review to assist in this determination. If the staff's final determination is that regular inservice inspections will be necessary to assure that the flaw size remains well below the "critical" level, a NUREG document will be written to provide guidance for acceptable methods and frequencies of inspection.

As an alternative or adjunct to the inspection, there exists a means of positive determination of adequate or inadequate toughness. This involves the collecting of steel samples from the locations of questionable toughness. Such samples would then be tested under laboratory conditions to determine quantitative levels of toughness. Expertise will be available in the implementation review to assist in the determination of advisability of sample withdrawal and the interpretation and application of sample results.

If none of the preceding measures provide positive assurance of adequate protection against brittle failures, a decision will be made regarding the need for ancillary heating or other corrective measures. The staff does not presently anticipate that any drastic measure, such as steel replacement, will be necessary to resolve the toughness issue. The matter of stress-corrosion cracking in high-strength steels is being pursued separately, at one operating reactor, by inspection of the maraging steel used in its supports. High-strength steels at other operating reactors will be reviewed during plant-specific implementation. Questions addressing the presence of these steels in applicable plants are included in Appendix D.

The staff concludes that the implementation plan represents an effective means of ascertaining, or assuring, adequate fracture toughness of the materials of PWR steam generator and reactor coolant pump supports.

FIGURE 1
PLAN FOR THE IMPLEMENTATION OF A-12 FRACTURE TOUGHNESS OF PWR COMPONENT SUPPORTS



PART II - POTENTIAL FOR LAMELLAR TEARING OF SUPPORT MATERIALS

5. INTRODUCTION AND STATEMENT OF PROBLEM

The Welding Institute publication entitled "Lamellar Tearing in Welded Steel Fabrication" defines lamellar tearing as:

> ... a cracking phenomenon which occurs beneath welds and is principally found in rolled steel plate fabrications. The tearing always lies within the parent plate, often outside the transformed (visible) heat-affected zone (HAZ) and is generally parallel to the weld fusion boundary. Lamellar tearing occurs at certain critical joints usually within large welded structures involving a high degree of stiffness and restraint. Restraint may be defined as a restriction of the movement of the various joint components that would normally occur as a result of expansion and contraction of weld metal and adjacent regions during welding.

The issue of lamellar tearing was also discussed during the licensing of North Anna Units 1 and 2. The staff's concern was that flaws existed in the North Anna support structures during construction and prior to operation. These flaws were subsequently detected and removed during inspection and rewelding of the supports.

Lamellar tearing is a ductile failure of the parent steel and occurs while the steel is cooling after the welding process. The tearing serves to relieve the tensile stresses imparted during the welding process. Such stresses, and the subsequent tearing, can be directly related to the welding method (heat input), the difference in strength between base and weld metals (weld metal typically much stronger), the amount of restraint of the welded joint, the geometry (configuration) of the joint itself, and other factors noted in Appendix C.

5.1 History of Lamellar Tearing and Unresolved Questions

As expanded upon in Section 5.0 of Appendix C, lamellar tearing has been in existence ever since the advent of welded structural steel construction. However, because of its nature as a subsurface flaw, it was relatively difficult to detect until there was significant advancement in the sensitivity and reliability of ultrasonic testing (UT). Thus, its mention in the literature, and its assumed occurrence, has until recently been relatively rare

Although it is not known to be a common defect, lamellar tearing has resulted in only one known failure, as determined by an extensive literature survey performed by Sandia and documented in Appendix C. However, in spite of this evident lack of failure attributable to lamellar tearing, the staff remains concerned because of unanswered questions involving the energy-absorbing capability of lamellar-torn joints and methods to avoid lamellar tearing. Their resolution is considered important in the long term, since the information gained from lamellar tearing research could result in advancements in materials selection, structural design, and welding process variables so that lamellar tearing is minimized.

For the short term, the staff has determined that, although there are outstanding questions, there is no reason to curtail the licensing or operation of any reactor due to support structure lamellar tearing considerations.

Both the research program and the acceptability of continued licensing and operation are discussed in the following section.

6. STUDIES IN PROGRESS AND JUSTIFICATION FOR CONTINUED REACTOR OPERATION AND LICENSING

As previously noted, lamellar tearing, although common in construction, has resulted in only one documented failure during service. This is in part due to general industry reaction to flaws found during construction: if found, they are to be removed. The Sandia report did point out the need for additional study to determine the residual strength of lamellar-torn joints.

The staff has acted upon this suggestion and has initiated a research program. The research project will include investigation of the means of initiating lamellar tears in the support materials of interest and then examining of their extension under normal loading conditions. Upon formation of the tears, the material specimens will then be tested in order to determine the remaining load-carrying capacity and significance of the tears as initiating defects for rapidly propagating fracture (brittle failure).

The program will also involve efforts to enhance the ability of non-destructive examination techniques to detect lamellar tearing, if deemed necessary by the results of the initial (residual strength) effort.

Finally, the staff will ask the research contractor to provide recommendations for fabrication requirements, design requirements, and manufacturing/assembly procedures that will minimize the introduction of lamellar tearing.

The staff has concluded that the research program will resolve the outstanding questions regarding lamellar tearing, and has determined that continued licensing and operation are justified during the course of the program. This is based on the knowledge that lamellar tearing is not as urgent a problem as previously contemplated (based on the lack of service failures) and the staff's conclusion that the likelihood of support failure due to lamellar tearing is low. The latter conclusion is drawn from the knowledge that applied stresses during operation are low and the probability of an initiating event (imparting large stresses to a torn joint) is very low. The staff also considers lamellar tearing to be a lower order failure mechanism than others that are possible in heavy weldments (e.g., weld toe cracking).

Based on these considerations, the staff determined that lamellar tearing as a generic issue could be separated from the A-12 generic task. Furthermore, the staff has concluded that action by licensees and applicants regarding lamellar tearing may be deferred until the research program has been completed. If this program should provide unexpected and unfavorable information regarding residual strength of lamellar-torn joints, the staff will take appropriate action such as requiring inspection (and repair, if necessary) of applicable supports.

APPENDIX A

Task A-12

FRACTURE TOUGHNESS AND POTENTIAL FOR LAMELLAR TEARING OF STEAM GENERATOR AND REACTOR COOLANT PUMP SUPPORTS

Lead NRR Organization:	Division of Operating Reactors (DOR)
Lead Supervisor:	Darrell G. Eisenhut, Deputy Director, DOR
Task Manager:	Dick Snaider, SEP/DOR
Applicability:	Pressur[illegible] Water Reactors
Projected Completion Date:	August 1979

1. DESCRIPTION OF PROBLEM

During the course of the licensing action for North Anna Power Station Unit Nos. 1 and 2, a number of questions were raised as to the potential for lamellar tearing[1] and low fracture toughness of the steam generator and reactor coolant pump support materials for those facilities. Two different steel specifications (ASTM A 36-70a and ASTM A 572-70a) covered most of the material used for these supports. Toughness tests, not originally specified and not in the relevant ASTM specifications, were made on those heats for which excess material was available. The toughness of the A 36 steel was found to be adequate, but the toughness of the A 572 steel was relatively poor at an operating temperature of 80°F. In the case of the North Anna Unit Nos. 1 and 2, the applicant has agreed to raise the temperature of the ASTM A 572 beams in the steam generator supports to a minimum temperature of 225°F prior to reactor coolant system pressurization to levels above 1000 psig. Auxiliary electrical heat will be supplied as necessary to supplement the heat derived from the reactor coolant loop to obtain the required operating temperature of the support materials.

Since similar materials and designs have been used on other nuclear plants, the concerns regarding the supports for the North Anna facilities may be applicable for other PWR plants. It was therefore considered necessary to reassess the fracture toughness of the steam generator and reactor coolant pump support materials for all operating PWR plants and those in CP and OL review.

Lamellar tearing may also be a problem in those support structures similar in design to North Anna. This possibility will be investigated on a generic basis. Although recently completed studies provided no conclusions regarding residual strength in a lamellar-torn joint, the staff is satisfied that continued operation of PWR facilities is safe in that there has been only one documented inservice failure attributed to lamellar tearing and this failure occurred on often-stressed truck brakes.

The scope of this program is limited to PWR steam generator and reactor coolant pump supports. Another program, ASYMMETRIC LOCA LOADS (A-2) will investigate vessel supports as part of its scope. As part of that effort, a review of the need for including BWR vessel supports is being undertaken.

[1]Lamellar tearing is a cracking phenomenon that occurs beneath welds and is principally found in rolled steel plate fabrications. The tearing always lies within the parent plate, often outside the transformed (visible) heat-affected zone (HAZ) and is generally parallel to the weld fusion boundary. Lamellar tearing occurs at certain critical joints usually within large welded structures involving a high degree of stiffness and restraint. Restraint may be defined as a restriction of the movement of the various joint components that would normally occur as a result of expansion and contraction of weld metal and adjacent regions during welding ("Lamellar Tearing in Welded Steel Fabrication," The Welding Institute).

2. PLAN FOR PROBLEM RESOLUTION

A preliminary survey of operating PWR plants was made in May 1976 to determine the initial scope of this problem. Results indicated that five units have designs similar to North Anna and that 12 units use A 36 materials. No plants which were surveyed used the A 572 material.

The staff concluded that, depending on the heat treatment of the A 36 material, a potential material toughness problem existed. In addition, it was determined that other materials used in the design of steam generator and pump supports have never been tested to determine toughness properties. Therefore, the potential "toughness problem" may exist for operating plants that did not use A 36 or A 572. As noted above, the potential for lamellar tearing may also exist for certain support structures.

Based on the above, the continuing action plan for resolution of this concern for operating PWRs was as follows:

A. Send a generic letter to all PWR licensees and selected OL applicants stating NRC concerns and requesting information on the design, materials, fabrication and inspection of the steam generator and reactor coolant pump supports for each plant. This was completed in late 1977.

B. Based on information supplied by the licensees and with the aid of the consultant, categorize the support design and materials as far as practical and select typical designs for further study. This has been completed. The consultant's report is presently being prepared for transmittal.

C. Complete preliminary review of typical designs and inform each applicable PWR licensee of the concerns on his particular support system. This implementation phase shall be accomplished with the aid of the consultant.

D. Utilizing input from consultant, develop and issue specific guidance for resolution of the problems discovered. This will be a joint DSS/DOR task and will result in the issuance of a NUREG document and/or other appropriate document. Work on the NUREG document will begin after receipt of the consultant's final report.

   Subsequent case-by-case resolution (implementation) will involve requiring those applicants or licensees for whose facility(ies) a problem exists to either: (1) demonstrate that safety margins are not lower than anticipated or (2) propose a solution to the problem in accordance with the criteria developed in step d above.

As noted in Section 1, no conclusion has been drawn regarding the severity of lamellar tearing and its affects at any of the PWRs reviewed.

Although the staff has concluded that plants are safe to continue operation, the lamellar tearing issue will remain incomplete until the completion of ongoing university studies which are unrelated to this generic issue. Because of the long-term nature of these studies, the lamellar tearing issue will be separated from the remainder of Generic Technical Activity A-12 but will be retained as a still-active technical issue. The priority assigned to this technical issue will be determined in the near future.

3. BASIS FOR CONTINUED PLANT OPERATION AND LICENSING PENDING COMPLETION OF TASK

As indicated in Section 2, the staff anticipates that the result of this task will be the issuance of a NUREG document and Standard Review Plan revisions which will delineate guidance and requirements for the selection of materials and the construction of reactor coolant pump and steam generator support structures. The documents will also address preservice inspection requirements for plants in the operating license stage and inservice inspection requirements for operating reactors.

A preliminary survey of operating PWRs was performed in late 1976. Based on the results of this survey and the information received to date as part of this task, we have determined that additional investigation of certain facilities is prudent. Presently, there is no ASME Code requirement for inspection of the steam generator supports, although the establishment of such a requirement is being considered. The ASME Code requires visual inspection once every ten years for reactor coolant pump supports. As noted above, the staff will consider establishing additional guidance and requirements for inservice inspection of these supports as part of the implementation portion of this task, with the assistance of consultant nondestructive examination expertise.

The staff considers that continued operation of all PWRs is warranted during this completion and implementation phase, because support failure is not expected to occur except under the unlikely combination of (1) an initiating event determined to be of very low probability (normal operating stresses are very low), (2) nonredundant and critical support member(s) of low-fracture toughness (many supports contain redundant members), (3) member operating temperature low enough that upper-shelf energy absorption (where fracture toughness properties are best) is not reached, and (4) a flaw of such large size that the stresses imparted during (1) above would be of such intensity that crack arrest would not occur and the member(s) would fail in a brittle manner.

As noted in Section 2, the lamellar tearing issue will be continued as an open item until the various university studies are completed. However, and also as noted in Section 1, the staff considers continued operation of PWRs during this study period to be acceptable, based on the fact that the consultant's review of approximately 400 related documents only revealed one instance of known failure, which occurred on often-stressed truck brakes. Again, applied stresses during normal operation are low and the probability of an initiating event is very low. Additionally, the staff considers lamellar tearing to be a lower order failure mechanism than others that are possible in heavy weldments, such as weld toe cracking.

Based on the foregoing, the staff has concluded that continued operation of operating reactors and licensing of plants in the operating license review stage will not present an undue risk to the health and safety of the public pending completion of the task. Further, based on the anticipated completion date for this task, the task results will be available well in advance of the operation of any plant currently under construction permit review.

4. NRR TECHNICAL ORGANIZATIONS INVOLVED

A. Engineering Branch, Division of Operating Reactors. Has lead responsibility for review of data generated from licensee responses, control of and coordination with consultant organization, coordination with DSS in development and issuance of criteria, and control of implementation on facilities having possible material problems.

Manpower Estimates: 0.6 man-year FY 1979.

B. Materials Engineering Branch, Division of Systems Safety. Review information received from operating units and problems identified during review. Coordinate with DOR in development and issuance of criteria.

Manpower Estimates: 0.2 man-year FY 1979.

C. Task Manager, Division of Operating Reactors. Has overall responsibility for coordination of DOR and DSS technical tasks and for the development and issuance of criteria documents. Provides assistance as required during implementation.

Manpower Estimates: 0.3 man-year FY 1979

5. TECHNICAL ASSISTANCE

Technical assistance for the DOR program is required to provide continuing expertise in evaluating the potential for fracture toughness of the support materials. The work will include:

A. Assisting in the formulation of information requests to, evaluation of responses from, and decisions regarding further action on, those plants to be identified in the forthcoming report as having materials of questionable fracture toughness.

B. Evaluating responses of those plants from which information was not received in time for full evaluation under the first phase of the program (six plants).

C. Providing assistance in formulation of questionnaires to, and in evaluation of responses from, PWRs recently licensed or soon to be licensed and on which complete review has not been accomplished.

D. Providing technical expertise in the area of nondestructive examination of the support structures, particularly in the assessment of ultrasonic testing efficacy. This task will also involve providing recommendations for changes to inservice inspection requirements to incorporate support inspection.

A consultant will be selected for the implementation work. We estimate costs to be $200,000 for FY 1979 and FY 1980.

6. INTERACTIONS WITH OUTSIDE ORGANIZATIONS

Individual licensees of PWR facilities and applicants for PWR licenses: All licensees of operating PWRs at program commencement were contacted to gather information. Those PWRs not already reviewed will be contacted as part of the implementation phase, as noted above. Some licensees will become more involved in this study due to the need for site visits and/or the discovery of material problems at their particular facility(ies). Further interaction will be a function of the results of our continuing review.

7. Assistance Requirements with Other NRC Offices

The Office of Standards Development intends to commence, in FY 1979, work on a program involving Fabrication and Examination of Component Supports. Although an effort is presently being made to incorporate specific guidance in the ASME Code, this new program may result in issuance of a Regulatory Guide.

8. Potential Problems

None.

APPENDIX B

INFORMATION REQUESTED FROM REACTOR LICENSEES AND SELECTED LICENSE APPLICANTS PURSUANT TO THE RESOLUTION OF GENERIC TECHNICAL ACTIVITY A-12

APPENDIX B

INFORMATION REQUESTED FROM REACTOR LICENSEES
AND SELECTED LICENSE APPLICANTS PURSUANT
TO THE RESOLUTION OF GENERIC TECHNICAL ACTIVITY A-12

1. Provide engineering drawings of the steam generator and reactor coolant pump supports sufficient to show the geometry of all principal elements. Provide a listing of materials of construction.

2. Specify the detailed design loads used in the analysis and design of the supports. For each loading condition (normal, upset, emergency and faulted), provide the calculated maximum stress in each principal element of the support system and the corresponding allowable stresses.

3. Describe how all heavy section intersecting member weldments were designed to minimize restraint and lamellar tearing. Specify the actual section thicknesses in the structure and provide details of typical joint designs. State the maximum design stress used for the through-thickness direction of plates and elements of rolled shapes.

4. Specify the minimum operating temperature for the supports and describe the extent to which material temperatures have been measured at various points on the supports during the operation of the plant.

5. Specify all the materials used in the supports and the extent to which mill certificate data are available. Describe any supplemental requirements such as melting practice, toughness tests and through-thickness tests specified. Provide the results of all tests that may better define the properties of the materials used.

6. Describe the welding procedures and any special welding process requirements that were specified to minimize residual stress, weld and heat affected zone cracking and lamellar tearing of the base metal.

7. Describe all inspections and non-destructive tests that were performed on the supports during their fabrication and installation, as well as any additional inspections that were performed during the life of the facility.

APPENDIX C

SANDIA LABORATORIES REPORT

(SAND78-2347)

FRACTURE TOUGHNESS OF PWR COMPONENT SUPPORTS

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Tables

Abbreviations

AE	Architect/Engineer
AISI	American Iron and Steel Institute
ASTM	American Society for Testing of Materials
AWS	American Welding Society
COD	Crack Opening Displacement
CVN	Charpy V-notch
DWTT	Drop Weight Tear Test
HAZ	Heat Affected Zone
HSLA	High Strength Low Alloy
K_{Ic}	Critical Plane Strain Stress Intensity Factor (Static)
K_{Id}	Critical Plane Strain Stress Intensity Factor (Dynamic)
KSI	Kilo pounds per Square Inch
LOCA	Loss of Coolant Accident
NDE	Non-Destructive Evaluation
NDT	Nil-Ductility temperature
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam System Supplier
PCC	Pre-cracked Charpy Test
PSIG	Pounds per Square Inch - Gauge Pressure
PWHT	Post Welding Heat Treatment
PWR	Pressurized Water Reactor
Q&T	Quenched and Tempered
ST	Short Transverse
STRA	Short Transverse Tensile Specimen Reduction of Area Measurement
UT	Ultrasonic Testing

Figures

Abstract

The Fracture Toughness of Component Supports Program at Sandia Laboratories, Albuquerque, New Mexico, was formally initiated in late September 1977. The objective of the program was to perform a generic fracture toughness evaluation of materials used in operating Pressurized Water Reactor (PWR) component supports. Historically, the program was initiated as a result of experiences that occurred during the licensing of the Virginia Electric Power Company North Anna Station.

The materials used in the component supports are classified according to three categories: 1) structural materials, 2) weld consumables, and 3) bolting materials. A further breakdown of the structural materials separates them into cast forms and wrought forms. Wrought forms will include plates, shapes (I-beams, H-beams, channels, etc.), pipes, forgings, bar, and wire cable. The wrought materials can be further broken down into the following subcategories:

a. Plain carbon (mild) steel
b. Carbon-manganese steel
c. High-strength low-alloy steel (HSLA)
d. Low alloy (non quenched and tempered) steels
e. Quenched and tempered steels

Material property data from numerous literature sources for these steels were assessed. As a result of the literature assessment, the following breakdown of the materials into groups is made. Where data is not available, a qualitative assessment has been made. The grouping was based mainly upon whether the average nil ductility temperature + 2σ was above 75°F (Group I), below 75°F (Group II), or well below 75°F (Group III).

Based upon the grouping of material in operating reactor supports and preliminary plant specific assessments, the plants were placed in groups as follows:

<u>Group I</u>

Millstone 2
Palisades
Crystal River 3
Davis-Besse 1
Rancho Seco 1
Three Mile Island 1
Surry 1 & 2
St. Lucie 1
J. M. Farley 1 & 2
Kewaunee
Point Beach 1 & 2
Prairie Island 1 & 2
Indian Point 2 & 3
Yankee Rowe
Ft. Calhoun 1
Maine Yankee

Group II

Beaver Valley 1	H. B. Robinson 2
Oconee 1, 2 & 3	Trojan
Calvert Cliffs 1 & 2	R. E. Ginna
Haddam Neck	Arkansas 1

Group III

D. C. Cook 1 & 2
Zion 1 & 2
Salem 1 & 2

The groupings imply a level of confidence, exclusive of lamellar tearing, for the support structures in each of the plants. Group III plants are considered to be as good as careful, reasonable engineering practice can produce.

Critical flaw sizes for representative component geometries are assessed and susceptibility to lamellar tearing is qualitatively evaluated for representative structures.

The next step in evaluating the fracture toughness of operating PWR component supports would be to demonstrate that Group I plants can be shown to be of adequate fracture toughness. Methods to perform this Phase II evaluation would require a detailed evaluation of Group I plants, including various aspects of the following:

1. More complete utility responses,
2. Measurement and analysis of operating temperatures,
3. Property characterization of in-place materials,
4. Stress analysis of critical locations,
5. In-service inspection of critical locations,
6. Testing for lamellar tearing, and
7. Fundamental materials research.

FRACTURE TOUGHNESS OF PWR COMPONENT SUPPORTS*

1.0 Introduction

The Fracture Toughness of Component Supports Program at Sandia Laboratories, Albuquerque, NM, was formally initiated in late September, 1977. The objective of this program was to perform a generic evaluation of materials used in operating Pressurized Water Reactor (PWR) component supports. Historically, the program was initiated as a result of experiences that occurred during the licensing of the Virginia Electric Power Company North Anna Station.

During the course of the licensing action for North Anna Power Station Units 1 and 2, a number of questions were raised as to the potential for lamellar tearing and low fracture toughness of the steam generator and reactor coolant pump support materials for that plant. Two different steel specifications (ASTM A-36-70a and ASTM A572-70a), covered most of the material used for these supports. Fracture toughness tests, not originally specified and not in the relevant ASTM specifications, were made on those heats for which excess material was available. The toughness of the A-36 steel was found to be adequate, but the toughness of the A-572 steel was relatively poor at an operating temperature of 80°F. For the North Anna case, Virginia Electric Power Company agreed to raise the temperature of the ASTM A-572 beams in the steam generator supports to a minimum temperature of 225°F prior to reactor coolant system pressurization to levels above 1000 psig. Auxiliary electric heat

*This work is supported by the U.S. Nuclear Regulatory Commission, Division of Operating Reactors.

will be employed to supplement the heat derived from the reactor coolant loop as necessary to obtain the required operating temperature of the structures.

Since similar materials and designs have been used on other nuclear plants, the concerns raised on the component supports for the North Anna plant were thought to be applicable to other operating PWR plants. Consequently, Sandia Laboratories, Albuquerque, New Mexico, was requested by the Division of Operating Reactors of the U.S. Nuclear Regulatory Commission (NRC) to provide technical assistance in evaluating the potential for lamellar tearing and low fracture toughness of the support materials of operating PWR plants. The technical assistance was to include:

a. Categorizing the support designs and materials (as far as practical) and selecting typical designs for further study;

b. Performing a literature search for fracture toughness and lamellar tearing data on the materials in question;

c. Evaluating typical designs and selecting those materials which may have low fracture toughness or a potential for lamellar tearing; and

d. Evaluating any proposed solutions to problems which may be identified.

In order to complete the generic objectives of the program, several tasks were scoped which included:

a. Data assembly and classification of operating reactor component supports;

b. Literature assessment of fracture toughness data and material evaluation;

c. Evaluation of the brittle failure potential of support materials;

d. Evaluation of the potential for lamellar tearing in component supports.

The results of this generic evaluation are summarized in the following sections.

2.0 Operating Plant Data

2.1 Data Desired

In order to assess the steam generator and reactor coolant pump support materials of operating PWR plants, information was required on materials selected, support design, fabrication details, and tests performed. At the same time that the Fracture Toughness of PWR Component Supports program was initiated at Sandia Laboratories, the NRC sent a request for information to each operating PWR licensee (a total of 41 reactors). The following information was requested from each licensee within sixty (60) days after receipt of the letter (September 1977):

1. Provide engineering drawings of the steam generator and reactor coolant pump supports sufficient to show the geometry of all principal elements. Provide a listing of materials of construction.

2. Specify the detailed design loads used in the analysis and design of the supports. For each loading condition (normal, upset, emergency and faulted), provide the calculated maximum stress in each principal element of the support system and the corresponding allowable stresses.

3. Describe how all heavy section intersecting member weldments were designed to minimize restraint and lamellar tearing. Specify the actual section thicknesses in the structure and provide details of typical joint designs. State the maximum design stress used for the through-thickness direction of plates and elements of rolled shapes.

4. Specify the minimum operating temperature for the supports and describe the extent to which material temperatures have been measured at various points on the supports during the operation of the plant.

5. Specify all the materials used in the supports and the extent to which mill certificate data is available. Describe any supplemental requirements such as melting practice, toughness tests and through-thickness tests specified. Provide the results of all tests that may better define the properties of the materials used.

6. Describe the welding procedures and any special welding process requirements that were specified to minimize residual stress, weld and heat affected zone cracking and lamellar tearing of the base metal.

7. Describe all inspections and non-destructive tests that were performed on the supports during their fabrication and installation, as well as any additional inspections that were performed during the life of the facility.

Complete information for each operating plant on the seven requests was expected to provide sufficient data to perform a plant evaluation.

2.2 Data Obtained

Information received from thirty-six (36) operating reactors in response to the NRC questions were included in this assessment. The plants for which replies were received are listed in Table 2.1. The detail and swiftness of the response varied greatly between utilities, however, sufficent information was received for a generic evaluation. The information received was condensed into a standardized format which is shown in Table 2.2. A summary for each of the plants is contained in Appendix A.

2.3 Structural Classification

Component supports were classified into the following structural categories:

a. Sliding Pedestal,

b. Skirt Supported,

c. Pin-Column,

d. Space Frame, and

e. Miscellaneous.

The design philosophy of the supports within each of these categories is similar but differences in materials and joint details make generalizations about a given category limited. Simplified examples of the

Table 2.1
Operating Reactors Supplying Responses

Palisades	Kewaunee
Millstone 2	D. C. Cook 1, 2
Maine Yankee	Prairie Island 1, 2
Calvert Cliffs 1, 2	Trojan
Crystal River 3	Zion 1, 2
Davis-Besse 1	J. M. Farley 1, 2
Oconee 1, 2, & 3	Beaver Valley 1
Three Mile Island 1	H. B. Robinson 2
Rancho Seco 1	Salem 1, 2
Arkansas 1	Yankee Rowe
Haddam Neck	Ft. Calhoun 1
R. E. Ginna	Surry 1, 2
Point Beach 1, 2	St. Lucie 1

Operating Reactors Not Included in all Assessments

Indian Point 2, 3	San Onofre 1
Turkey Point 3, 4	

Table 2.2

COMPONENT SUPPORT SUMMARY

PLANT ____________________

UTILITY	NSSS	AE	SUPPORT SUPPLIER

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS THROUGH THICKNESS

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT

non-miscellaneous component support classes are shown in Figure 2.1. The classification of the operating reactors into structural categories is listed in Table 2.3.

Table 2.3

Structural Classifications

<u>Sliding Pedestal</u> (5)

Palisades	Maine Yankee
Millstone 2	Calvert Cliffs 1, 2

<u>Skirt Supported</u> (9)

Crystal River 3	Rancho Seco 2
Davis-Besse 1	Arkansas 1
Oconee 1,2,3	Haddam Neck
Three Mile Island 1	

<u>Pin Column</u> (13)

R. E. Ginna	Prairie Island 1,2
Point Beach 1,2	Trojan
Kewaunee	Zion 1,2
D. C. Cook 1,2	J. M. Farley 1,2

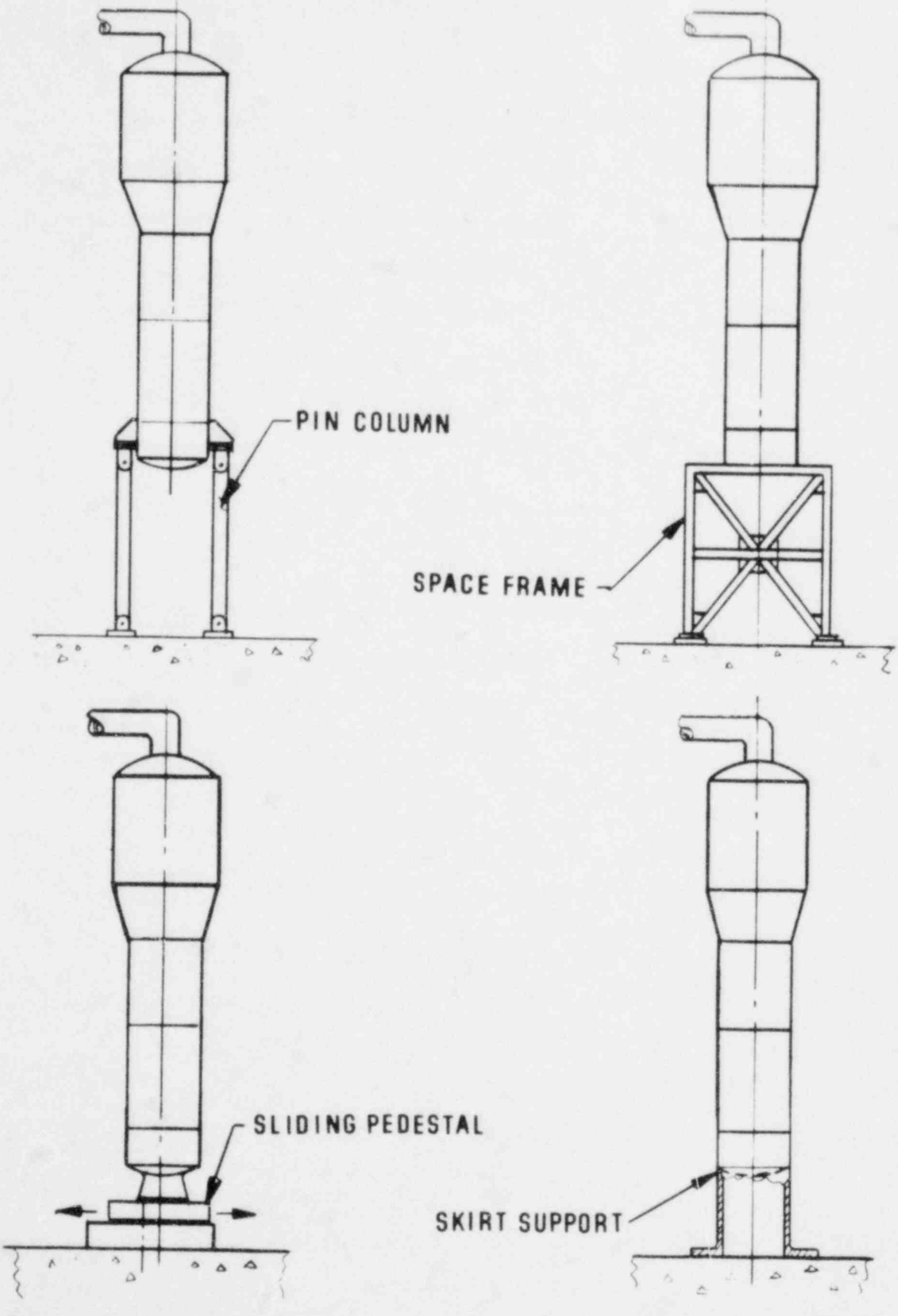
<u>Space Frame</u> (5)

Beaver Valley 1	Salem 1, 2
H. B. Robinson 2	Yankee Rowe

<u>Miscellaneous</u> (4)

Ft. Calhoun 1	St. Lucie 1
Surry 1,2	

FIGURE 2.1
COMPONENT SUPPORT CLASSES



3.0 Materials Classification

3.1 Forms

The materials used in the plants considered can be classified according to three categories: 1) structural materials, 2) weld consumables, and 3) bolting materials. A further breakdown of the structural materials separates them into cast forms and wrought forms. Wrought forms will include plates, shapes (I-beams, H-beams, channels, etc.), pipes, forgings, bar, and wire cable.

Table 3.1 lists the applicable specifications under which the various materials were procured.

Certain generic characteristics can be associated with wrought or cast structural materials that will affect their mechanical or chemical behavior in service. For example, cast materials are more isotropic in their strength and ductility than wrought materials, and are not susceptible to lamellar tearing. However, because cast materials have not undergone mechanical working, they tend to exhibit porosity, greater chemical segregation, and possibly coarser grain size (depending upon subsequent heat treatment).

The bolting materials listed in Table 3.1 are (with three exceptions A-306, A-307, and A-322) high strength, quenched and tempered grades. Because these materials are of high strength, and contain well-tempered martensitic microstructures, they would not be expected to show an abrupt ductile-brittle transition. For this reason, the quenched and tempered bolting materials will not be further evaluated for their brittle fracture characteristics. In addition, because of the way in which the ASTM specifications are written, the alloy used is not always explicitly identified, and

Table 3.1

Steels Utilized in PWR Component Supports

I. Structural Materials

ASTM Specifications

A-7	Steel for Bridges and Buildings
A-27	Mild-to-Medium Strength Carbon Steel Castings for General Application
A-36	Structural Steel
A-53	Welded and Seamless Steel Pipe
A-105	Forgings, Carbon Steel for Piping Components
A-106	Seamless Carbon Steel Pipe for High Temperature Service
A-148	High Strength Steel Castings for Structural Purposes
A-201	Carbon-Silicon Steel Plates of Intermediate Tensile Ranges for Fusion-Welded Boilers and Other Pressure Vessels
A-212	High Tensile Strength C-Si Steel Plates for Boilers and Other Pressure Vessels
A-216	Carbon-Steel Castings Suitable for Fusion Welding for High-Temperature Service
A-283	Low and Intermediate Tensile Strength Carbon Steel Plates of Structural Quality
A-284	Low and Intermediate Tensile Strength Carbon-Silicon Steel Plates for Machine Parts and General Construction
A-285	Pressure Vessel Plates, Carbon Steel, Low and Intermediate Tensile Strength
A-302	Pressure Vessel Plates, Alloy Steel, Mn-Mo and Mn-Mo-Ni
A-352	Ferritic Steel Castings for Pressure Containing Parts Suitable for Low Temperature Service
A-353	Pressure Vessel Plates, Alloy Steel, 9 percent Nickel, Double-Normalized and Tempered
A-387	Pressure Vessel Plates, Alloy Steel, Cr-Mo
A-441	High Strength Low Alloy Structural Mn-V Steel
A-461	Precipitation Hardening Alloy Bars, Forgings, and Forging Stock for High Temperature Service
A-501	Hot Formed Welded and Seamless Carbon Steel Structural Tubing
A-508	Quenched and Tempered Vacuum-Treated Carbon and Alloy Steel Forgings for Pressure Vessels
A-514	High Yield Strength, Quenched and Tempered Alloy Steel Plate, Suitable for Welding
A-515	Pressure Vessel Plate, Carbon Steel for Intermediate and Higher Temperature Service
A-516	Pressure Vessel Plates, Carbon Steel, for Moderate and Lower-Temperature Service
A-517	Pressure Vessel Plate Alloy Steel, High Strength Quenched and Tempered
A-533	Pressure Vessel Plates, Alloy Steel, Quenched and Tempered, Mn-Mo, and Mn-Mo-Ni
A-537	Pressure Vessel Plates, Heat-Treated, Carbon-Manganese-Silicon
A-543	Pressure Vessel Plates, Alloy Steel, Quenched and Tempered, Ni-Cr-Mo
A-572	High Strength Low Alloy Columbium-Vanadium Steels of Structural Quality
A-588	High Strength Low Alloy Structural Steel with 50 ksi Minimum Yield Point to 4 in. thick
A-603	Zinc-coated Steel Structural Wire Rope
A-618	Hot-formed Welded and Seamless High Strength Low-Alloy Structural Tubing

Table 3.1 (Continued)

AISI Specifications

1015	Plain Carbon Steels	.15C
1018	Plain Carbon Steels	.18C
1020	Plain Carbon Steels	.20C
1117	Resulphurized free-machining steel	.17C

Miscellaneous Specifications

Vascomax 250, " 300, " 350 — Ultra-High Strength Maraging Steels

Camvac 200

Carpenter Custom 455 Martensitic Stainless Steel

II. Weld Consumables

AWS Welding Specifications

E 7015
E 7016
E 7018, E 8016 C-1, E 8016 C-2, E 8018 C-1, E 8018 C-2 — Manual Metal-Arc Welding Electrodes
E 8018 G
E 8018 C-3
E 11018-M
E 120 S-1 Metal - Inert Gas Electrode
E 70 T-1 Metal - CO_2 Electrode
E 70 T-5

F 70 EL-12 Submerged-Arc Welding
F 71 EL-12
F 70 EM-12
F 70 EM-12K

III. Bolting Materials

A-193	Alloy Steel and Stainless Steel Bolting Materials for High-Temperature Service
A-194	Carbon and Alloy Steel Nuts for Bolts for High-Pressure and High-Temperature Service
A-306	Carbon Steel Bars Subject to Mechanical Property Requirements
A-307	Carbon Steel Externally and Internally Threaded Standard Fasteners
A-322	Hot-Rolled Alloy Steel Bars
A-325	High Strength Bolts for Structural Steel Joints, Including Suitable Nuts and Plain Hardened Washers
A-354	Quenched and Tempered Alloy Steel Bolts, Studs, and Other Externally Threaded Fasteners
A-490	Quenched and Tempered Alloy Steel Bolts for Structural Steel Joints
A-540	Alloy Steel Bolting Materials for Special Applications
A-563	Carbon Steel Nuts
A-574	Alloy Steel Socket-Head Cap Screws

thus the manufacturer may choose from a wide variety of steels which can meet the criteria of size, strength, quenching medium and minimum tempering temperature.

The normal use of bolting materials does suggest that delayed environmental cracking under static load (i.e., stress corrosion cracking) be considered. Because of the close similarity of all the low alloy quenched and tempered steels, as long as the specified yield strength is less than ~ 180 ksi, this problem is not considered to be present. However, if ultra high strength alloy steels are specified at levels of yield strength of 200 ksi or greater, and used such that a constant pre-load is present, a warning of possible stress-corrosion cracking is noted.

3.2 Categorization Into Groups

Although only two material grades were explicitly mentioned when this program was initially proposed (A-36 and A-572), the number of materials finally evaluated was substantially higher. Because of the inability to obtain sufficient data on all grades, similar grades of materials were grouped so that a better statistical treatment of the data obtained would be possible. Since distinct differences occur among the steels considered on the basis of microstructure, alloy content, and processing, alternative grouping schemes different from the one chosen are possible depending upon which characteristics are considered primary.

The first division chosen was cast vs wrought materials. The cast materials include grades A-27, A-148, A-216, A-352, and the welding consumables. The wrought materials include all others listed in

Table 3.1. Since the number of cast grades is low, they are treated by grade in Appendix B. The large number of wrought grades prevented such individual treatment; thus additional division into groups was necessary. The groups chosen reflect the microstructure differences and material strengthening mechanisms utilized. The wrought material groups are:

a. Plain carbon (mild) steel
b. Carbon-manganese steel
c. High-strength low-alloy steel (HSLA)
d. Low alloy (non quenched and tempered) steels
e. Quenched and tempered Steels

The alloy grades which fall within these groups are listed in Table 3.2. A grade may occur in more than one grouping depending upon the heat-treatment specified. Within the carbon-manganese and HSLA grouping, a further subdivision is made depending upon whether normalization is applied. As will be seen later, this makes a substantial difference. An alternative grouping was also evaluated dividing the first two groups (a and b) into semi-killed and killed grades. The grouping listed above was finally chosen because it more consistently reflects the grouping rationale applied to the last three groups, that of strengthening mechanism, as opposed to steelmaking practice.

For some materials, no data could be found. In this case, evaluation of the material was made by noting which microstructure group the grade belonged to as indicated by the minimum requirements of the appropriate ASTM standards.

Table 3.2

Classification of Wrought Grades into Groups

Plain carbon: A-7, A-53, A-106, A-201, A-212, A-283, A-284
A-285, A-306, A-307, A-501, A-515

Carbon-manganese: A-36, A-105, A-516, A-537

High-strength low-alloy: A-441, A-572, A-588, A-618

Low alloy (not quenched & tempered): A-302, A-322, A-353, A-387

Quenched & tempered: A-193, A-194, A-325, A-354, A-461, A-490,
A-508, A-514, A-517, A-533, A-537, A-540,
A-543, A-563, A-574.

4.0 Plant Assessment Concerning Brittle Failure

4.1 Materials Parameters Available

It has been realized fo many years that strength of materials-type design considerations are inadequate to provide complete assurance against catastrophic brittle failure in steel structures. The attempt to correct for this situation by including "factors of safety" can never be totally acceptable unless uneconomically large factors are assumed. Thus tests evolved to quantify resistance to brittle fracture. Among these are the notched tensile sample, the Charpy impact test in its various forms and modifications, the drop weight NDT (Nil Ductility Temperature) test, the DWTT (Drop Weight Tear Test), and the fracture toughness (K_{Ic} or Crack Opening Displacement [COD]) test. This evolution has led from a purely qualitative service experience-based quantity to an explicitly quantitative design procedure for high strength materials.

Recent interest in the extension of fracture toughness techniques to low-strength materials has resulted in considerable research. However, it cannot yet be stated that routine fracture toughness testing has arrived for low strength materials in temperature regimes where they exhibit large amounts of plasticity. This is not a major obstacle to this assessment however, because if major amounts of plasticity are present, the structures concerned are probably safe. They have been designed by methods which postulate ductile overload as a failure criterion. Within those methods, factors of safety are generally included which allow design loads only modestly beyond yield strength. In addition, the value of yield strength used is generally conservatively specified for the particular grade of steel chosen.

Thus, the fracture mechanics approach will be used to estimate allowable flaw size only if the materials analyzed are in the brittle condition where linear elastic fracture mechanics is applicable.

4.2 Parameters Chosen

Three different test parameters were chosen as applicable to this assessment. The first is the Charpy V-notch (CVN) test. The CVN test is commonly used as a screening test to eliminate undesirable materials. As such, those plants which maintained a minimum Charpy requirement for their materials of construction will be assumed to be constructed of adequate toughness materials, and placed in a higher quality category than those which did not specify any minimum. Additionally, welding consumables used according to AWS specifications requiring CVN testing were placed into a higher quality category for the same reason. The 15 ft-lb CVN value commonly specified as a minimum corresponds to a K_{Id} of ~ 43 ksi $\sqrt{in.}$, or K_{Ic} of ~ 74 ksi $\sqrt{in.}$, using correlations developed by Corten and Sailors (Ref. 4.1). The choice of which value to use will be discussed later in this section.

The second parameter, NDT, started out as a service-based criterion, but has since been analyzed according to fracture mechanics principles. Use of a material at its NDT provides assurance that small, but detectable, growing cracks will arrest at yield strength load levels. Preferably, a guarantee of arrest for any size crack is desired. This would give assurance that locally-embrittled regions could not cause catastrophic failure by allowing small cracks to grow to larger sizes. This is important because these locally embrittled regions may not be detectable by non-destructive inspection methods.

Such an assurance is obtained by allowing structures to be used only at temperatures from 60 to 120°F (depending upon thickness) above the highest NDT measured for the materials used. The converse approach, where materials are required to meet a maximum NDT specification, is also valid. Indeed, this latter approach is probably more desirable when the operating temperature is pre-determined.

This large crack arrest criterion appears to be less firmly based upon fracture mechanics principles, but instead appears to be the result of engineering experience.

The advantages of using the NDT approach are that it is a simple one-parameter criterion; it is a dynamic loading criterion, it has been around long enough so that substantial data have been generated; and it is ASTM standardized. The disadvantages are that it is not applicable to specific load-flaw size conditions other than that inherent to the test, and that certain types of materials (notably Q&T steels) may yield anomalous values due to the method of specimen preparation.

These two above-mentioned tests will be used in Section 4.7 to rank the materials used into three relative categories of toughness: Group I the least tough; Group II intermediately toughness; and Group III, the highest toughness. The PWR plants will then be ranked into three groups depending upon which materials are used, and also where and how these materials are used. The plants will be grouped in a manner similar to the materials grouping; i.e., Group I - highest brittle fracture susceptibility to Group III - least susceptibility.

Finally, the third parameter, fracture toughness (K_{Ic} or COD) will be used in an attempt to provide an improved assessment of the Group I plants by deciding upon critical crack lengths in representative geometries encountered in the various plants.

In using fracture toughness data the effect of strain rate has been shown to be important; for this reason dynamic data (K_{Id}) was used where available. Because of a lack of dynamic data, it was also necessary to use "corrected" static results. The strain rate effect is equivalent to a shifting of the entire K_{Ic} vs temperature curve to higher temperatures with increasing strain rate. The shift apparently occurs over a moderate range of strain rates and saturates both at very low and very high strain rate regimes. The shift between very low and very high rate data according to Barson (Ref. 4.2), is given by the equation:

$$T_{shift} = 210 - 1.5\,\sigma_{ys} \text{ (in °F)}$$

where σ_{ys} is the room temperature yield stress of the material in ksi. Other authors have found that this equation does not accurately predict their results (Ref. 4.3). Another equation has been proposed by Sunamoto, et al. (Ref. 4.4):

$$T_{shift} = 1.8 \exp(8.0 - .038\,\sigma_{ys}) \text{ (in °F)}$$

A comparison of these two equations is shown in the following table.

Table 4.1
Alternative Strain Rate Shift Values

σ_{ys}	Barsom	Sunamoto
40	150°F	228°F
60	120	156
80	90	107
100	60	73
120	30	50
140	0	34

It can be readily seen that substantial differences arise between the two equations. Barsom's equation is somewhat less conservative, i.e., it would predict slightly higher K_{Id} @ 75°F than Sunamoto's. It is not known why such differences exist, and further work needs to be done to better establish the relative shift between static and dynamic fracture toughness.

4.3 Minimum Operating Temperature

The minimum operating temperatures of the component supports in the plants are listed in Table 4.2. These temperatures were obtained from the responses by the utilities to the request for information by the NRC. Most of the minimum temperatures were estimates based upon the potential minimum ambient temperature in the containment location of the supports. Some plants estimated a higher support temperature based upon the proximity of the supports to the primary coolant system which would be at elevated temperatures during plant operation. For the initial generic plant evaluation, a minimum support operating temperature of 75°F was suggested by NRC personnel.

Table 4.2
Minimum Support Operating Temperatures

Palisades	100°F	Kewaunee	70°F
Millstone 2	115°F	D. C. Cook 1,2	60°F
Maine Yankee	89°F	Prairie Island 1,2	70°F
Calvert Cliffs 1.2	--	Trojan	90°F
Crystal River 3	--	Zion 1,2	71°F
Davis-Besse	50°F	J. M. Farley 1,2	120°F
Oconee 1,2,3	--	Beaver Valley 1	83°F
Three Mile Island 1	--	H. B. Robinson 2	65-70°F
Rancho Seco 1	--	Salem 1,2	70°F
Arkansas 1	50°F	Yankee Rowe	200°F
Haddam Neck	90-110°F	Ft. Calhoun 1	80°F
R. E. Ginna	120°F	Surry 1,2	83°F
Point Beach 1,2	85°F	St. Lucie 1	60°F

4.4 Data Summary

In this section will be found a highly condensed presentation of the data collected in this assessment. The reader is directed to Appendices B and C contain a more detailed presentation.

4.4.1 CVN Data

As noted in section 4.2 the CVN test was used only to indicate the requirement for material testing. This screening was considered more fundamental than the actual value of the CVN requirement (20 ft-lbs), which is however considered to approximate the NDT criterion. Any material which requires impact testing (CVN or other) is thus considered removed from Group I and placed into Group II or Group III.

Materials which must meet CVN requirements are:

Table 4.3
Materials With CVN Requirements

Cast Materials

ASTM A-352, Gr LC 3

Weld Consumables

AWS	E 7015, E 7016, E 7018
	E 8016-C1, E 8016-C2
	E 8018-C1, E 8018-C2, E 8018-C3
	E 11018-M
	F 71-EL 12
	F 72-EM 12K
	E 70-T1
	E 70-T5

Wrought Materials

ASTM	A-353
	A-508
	A-517 (this requirement was instituted in 1970 after some plants were already built)

4.4.2 NDT Data

The materials for which NDT data were collected were divided into groups outlined in section 3.2. Within a given group, the average ($\overline{NDT}$) and standard deviation (σ) were calculated where possible (a normal distribution was assumed). If this was not possible either an average value and an σ estimated was noted, or an upper bound value was given.

The tabulation of these values is given in Table 4.4. The $\overline{NDT} + 1.3\sigma$ and $\overline{NDT} + 2\sigma$ notations refer to the 90% and 95% confidence limits that NDT for any heat of steel of a given group is above this temperature.

Table 4.4
Computation of NDT Results

Material	$\overline{NDT}$		$\overline{NDT}$ + 1.3σ	$\overline{NDT}$ + 2σ
Cast Steels				
A-27, A-216 1"	- 6°F	12°F	10°F	18°F
(heat treated 1" condition)	35	17	57	69
A-352				max. -20
Wrought Steels				
all "mild" steels*	27	31	67	89
all "mild" steels except A-201	40	28	77	96
C-Mn*(as-hot rolled)	22	13	39	48
(normalized)	-28	18	- 5	8
HSLA* (as-hot rolled)	25**	12**	41**	49**
(normalized)	-50**	18**	-27**	-14**
low alloy non Q&T				
A-302	8	28	45	64
A-353				max. -320
A-387				65**
Quenched & Tempered				
A-508 Cl2				max. 40°F
A-514				max. -10°F
A-517				max. -20°F
A-533B Cl1				max. 20°F
A-537 Cl2				max. -60°F
A-543				max. -60°F

* See table 3.2 for ASTM specs included in this category
** See discussion in Appendix B

4.4.3 Fracture Toughness

Minimum values for fracture toughness of the material groups are indicated in Table 4.5. These are usually dynamic values or static values obtained at lower temperatures equivalenced via the Barsom temperature shift (see section 4.2). Data at the reference temperature, 75°F, was not always obtainable. If data was not obtainable, results at the nearest temperature available were used, or in some cases an extrapolation was made. Because of the limited data, these are not analyzed statistically; thus it may not be reasonable to use some of these values in design other than as a pessimistic worst case.

Table 4.5
Minimum Fracture Toughness Data @ 75°F

Plain Carbon	32 ksi $\sqrt{in}$
C/Mn	36 ksi $\sqrt{in}$
HSLA	36 ksi $\sqrt{in}$
Low Alloy (non Quenched and Tempered)	
A-302	30 ksi $\sqrt{in}$
A-353	150 ksi $\sqrt{in}$
A-387	65 ksi $\sqrt{in}$
Quenched and Tempered	
A-508	35 ksi $\sqrt{in}$
A-514/A-517	65 ksi $\sqrt{in}$
A-533	35 ksi $\sqrt{in}$
A-537	55 ksi $\sqrt{in}$
A-543	95 ksi $\sqrt{in}$
Other	
A-461, Gr 630	100 ksi $\sqrt{in}$

4.5 Metallurgical Embrittlement Phenomena

A number of embrittlement mechanisms operate in the steels included in this assessment. The most important ones are briefly discussed in the following sections.

4.5.1 Strain-Age Embrittlement

Strain age embrittlement occurs when two factors combine: plastic straining and diffusion of interstitial carbon or nitrogen atoms. The temperature cycling and consequent thermal strains of a weldment, (especially a multipass weldment) is thus an ideal situation to cause this type of embrittlement. Because increasing the amount of strain serves to aggravate the embrittlement (Ref. 4.5), the presence of cracks or notches (which concentrate strain) may cause embrittlement in steels not usually affected by the lower amount of strain present in a crack-free weld. Such embrittlement also occurs in the worst possible place, around a sharp flaw.

Fortunately, this type of embrittlement is easily reversed or not as acute in some steels (Ref. 4.6) (semi-killed steels are particularly susceptible). One can reduce the interstitial content (impractical for common structural materials, which rely upon carbon for strength, however), tie up the carbon or nitrogen with carbide or nitride formers, or eliminate the atmospheres of carbon or nitrogen around the dislocations by dispersing them with a thermal treatment. In effect, stress-relief annealing serves to minimize this problem. Thus, non-stress-relieved structures, or those in which peening are used would be most susceptible to this form of embrittlement which can raise ductile/brittle transition temperatures by up to 120°F (Ref. 4.7).

4.5.2 Stress-Relief Embrittlement

This form of embrittlement occurs in steels which precipitation harden during elevated temperature aging treatments (Ref. 4.8). The elements Chromium, molybdenum, copper, niobium, and vanadium are typically involved. Segregation of boron to prior austenite grain boundaries is also suggested (Ref. 4.9).

Of the steels being surveyed A-387, A-508, A-514/A-517, and A-533 contain appreciable amounts of these elements, and it is generally known that stress relief annealing in these grades of steel may cause problems. If this is necessary because of the particular structure involved or because of code requirements, it has been shown that specifying the weld metal yield strength to below that of the base material can help avoid cracking in severe cases. Using higher heat inputs or preheat during welding (Ref. 4.10) may also be beneficial.

For steels which are embrittled, but do not crack, there is an engineering trade-off to be considered. Admittedly the fracture toughness will decrease (for example in A-514/A-517 steels an increase of 60°F in the .015 inch lateral expansion CVN transition temperature can occur) however, because the level of residual stress is decreased the defect tolerance may actually increase (Ref. 4.11).

4.5.3 Temper Embrittlement

In this form of embrittlement, which is most serious in martensitic microstructures, segregation of tramp elements such as sulphur, phosphorus, antimony, arsenic, and tin to prior austenite grain boundaries occurs. The presence of specific element combinations can act to accelerate (such as Cr with P and Ni with Sb), or retard (addition of Mo) the kinetics of the process (Ref. 4.12). The main way to avoid temper embrittlement is to avoid those combinations of time and temperature which cause it, and to try to avoid steels with high content of tramp elements. The latter is impractical, as the concentration of the impurities at the grain boundaries can be very much higher than their overall concentrations. In cases where temper embrittlement is present, it can be reversed via appropriate heat treatment (reheating above the embrittling range). A rapid cooling from above the temper embrittlement range (700-1100°F) also avoids this problem; this may not be compatible with code practices, however. Steels which may show this problem are A-353, A-387, A-508, A-514/517, A-533 and A-543. Essentially, these are nearly all the Q&T steels (whether intentionally by heat treatment or unintentionally in the HAZ) with appreciable alloy content. It is not impossible to see an increase in transition temperature of 360°F in severe cases; although 90°F is probably more common (Ref. 4.13). However, these alloys usually have a very low transition temperature to start with.

4.6 Classification of Plants According to Materials Used

As a result of the literature assessment a breakdown of the materials into groups is made in Table 4.6. Where data are not available, a qualitative assessment has been made, and noted wi h an asterisk. The assessment was based mainly upon whether the expected $\overline{NDT} + 2\sigma$ was above 75°F (Group I), below 75°F (Group II), or well below 75°F (Group III). Material manufacturing or processing mistakes are not included in this grouping.

Operating a structure at or above its NDT temperature is really only a first level of safety; it concerns itself with prevention of fracture initiating from small cracks (~ 1/2"). Only by operating at a temperature significantly above NDT, (NDT + 120°F for the thicker materials of interest) can prevention via crack arrest capability be obtained. At an operating temperature of 75°F this cannot be

Table 4.6
Material Groups

Group I (highest susceptibility to brittle failure)

Cast materials:

A-27 (annealed condition)*
A-148 (annealed condition)*
A-216 (annealed condition)*

Wrought materials:

A-7
A-53*
A-105* (annealed condition)
A-106
A-212
A-283*
A-284*
A-285
A-306*
A-307*
A-515

High Risk of Stress-Corrosion Failure:

Vascomax 250, 300, 350
Custom 455 Stainless Steel

Group II (intermediate susceptibility to brittle failure)

Cast materials:

A-27 (heat-treated
A-148 (heat-treated)
A-216 (heat-treated)
F70-EL12*
F70-EM12*

Wrought materials:

AISI 1015, 1017, 1020*
A-36
A-105 (heat treated)
A-201
A-302
A-322
A-387
A-441 (as rolled)
A-501*
A-516
A-572 (as rolled)
A-588 (as rolled)
A-618 (as formed)*

Group III (least susceptibility to brittle failure)

Cast materials:

All other weld consumables in Table 3.1
A-352

Table 4.6 (cont'd)

Wrought materials:

A-193		A-353
A-194		A-461
A-325	Bolting	A-508
A-354	materials*	A-514
A-490		A-517
A-540		A-533
A-574		A-543
		A-603*
		Camvac 200*

*Qualitative assessment, based upon judgment of authors, no specific data available.

obtained except for the very toughest of the Group III materials, i.e., A-353, A-352, A-537, A-543, and even they would be questionable if a bad heat were encountered.

Using the above table, and the summary of materials information, a preliminary classification of the plants can be made. Based upon the materials used in construction, the operating plants for which responses were available were divided into three groups. The decision method follows. If impact test data of some form (usually CVN) were available, or the materials used were all in Group III, the structure was considered to be of the low susceptibility category; if not, then the grades of materials used were utilized to separate them into two other categories. If the materials were judged adequate (Group II or III), the plant was placed in the intermediate category, and if the structure contained any main structural members of an uncertain material (Group I), it was placed in the high susceptibility category.

The following Table 4.7 represents a breakdown into three categories of highest, medium, and lowest susceptibility to brittle fracture. This, however, does not include an absolute evaluation. (Within a group the order is not significant).

Table 4.7
Preliminary Assessment of Plant Groups

Group I Highest Susceptibility: (either poor materials [Group I], or poor processing)

Crystal River 3 Oconee 1,2,3 Rancho Seco 1 Three Mile Island 1	(contain A-515)
Davis-Besse 1	(contains A-515 and A-53 or A-106 on snubber attachments and Zn coated cable)
Indian Point 2,3	(A-53)
Ft. Calhoun 1	(A-307, nuts and bolts)
J. M. Farley 1,2	(Custom 455 bolts)
Kewaunee	(Kewaunee appears identical with Prairie Island, 250/300 grade maraging steel bolting)
Maine Yankee	(if A-27 base is heat-treated, which is not indicated, move to Group II)
Millstone 2	(A-515, A-106 in RCP)
Palisades	(A-212)
Point Beach I & II	(A-53, stress relieved A-514. Cogni zance of the stress relief problem was indicated as a concern of procedure qualification; heat-to-heat vari- ability may defeat this, however).
Prairie Island 1 & 2	(250/300 grade maraging bolting)
Salem 1,2	(300 grade maraging steel bolts)
St. Lucie	(contains A-515 on RCP snubber clevis, A-27 base heat-treatment has not been indicated in response)

Surry 1,2 (A-106, A-105, A-285, 300/350 grade maraged bolting)

Yankee Rowe (A-7)

Group II Intermediate Susceptibility: (probably acceptable materials [Category II & III] no testing)

Arkansas 1

Beaver Valley 1

Calvert Cliffs 1,2

Haddam Neck

R. E. Ginna

H. B. Robinson

Trojan

Group III Least Susceptibility: (untested exceptionally good materials [Group III], or tested materials)

D. C. Cook 1 & 2

Zion 1 & 2

These classifications are not final and are given further consideration below.

4.7 Detailed Consideration of Group I Plants

The plants which were tentatively placed in the first category based on materials alone were further examined in detail. The particular application of Group I materials was assessed. For example, a Group I material in a nameplate or a shim should not be of concern. The plants will be reviewed by structural categories (as listed in Table 2.3) and in alphabetical order within each category.

4.7.1 Sliding Pedestal

The sliding pedestal plants which were placed in Group I are Maine Yankee, Millstone 2 and Palisades.

Maine Yankee was placed in Group I because no information about the heat treatment condition of the steam generator base casting was provided. If the base was normalized or quenched and tempered, this plant could be moved to Group II. If the casting is in the annealed condition, reclassification can still occur if the temperature of the base is sufficiently high. Millstone 2 is retained in Group I after a detailed review. The A-106 and A-515 steel members in the primary coolant pump supports could not be located because the drawings supplied were unreadable. On the drawings which could be read the following materials which were not listed in the response to question 5 of the NRC request for information were found to be used in the structures:

A-572 Gr 50 as an alternative,
A-588 Gr B plates,
A-490 bar and hex nuts,
A-151 - 4140 shim plate, and
A-441 miscellaneous steel.

(The above are all Group II and III materials.)

Palisades uses A-212 steel, which caused it to be placed in Group I, and some materials such as the A-540 studs (4 ea. 5 in. dia.) in the coolant pump supports were not listed in the response to question 5 of the request. (However, this is a Group III material and is ranked better than the A-36 used elsewhere in the structure and would therefore not downgrade its classification.) The A-212 in the base flange of the steam generator support is a Group I material. However, this flange is near the hot primary coolant piping and steam generator body and would possibly have a high minimum operating temperature. This might move this plant from Group I into Group II if the higher temperature were verified.

4.7.2 Skirt Supported

The skirt supported structures considered in Group I were Crystal River 3, Davis-Besse 1, Oconee 1,2,3, Rancho Seco 1 and Three Mile Island 1.

The Crystal River coolant pump is stated to be supported by the piping so no support structure is used. The steam generator skirt material is acceptable but the flange and gussets are Group I materials (see Figure E15 in Appendix E). Because of the proximity to the hot generator and piping these items might be above 200°F during operation which would remove their brittle fracture susceptibility. There is no information about the upper support on the steam generator, so this structure would have to be retained in Group I until the upper support materials are examined during the plant-specific NRC review.

Davis-Besse 1 has A-515 and A-53 used in the steam generator lower lateral support. In particular, the A-515 is used in the snubber plate and snubber gusset and bumper on the support skirt. The A-53 is used to attach a rod eye of the 20 in. dia. hydraulic cylinder which attaches to a point near the parts above. It may be that these have been impact tested, however. The response is somewhat ambiguous as to whether the impact requirement was for the A-36 and A-516 over 5/8", or for all material over 5/8". The LOCA loads are the only severe loads, with compressive loads twice that of the tensile, a favorable consideration. The minimum operating temperature of these specific parts might be determined to be high enough to move this structure to Group II.

The cables which restrict the coolant pump motion also deserve some consideration. They are zinc coated and if this coating reaches temperatures near 500°F a chemical reaction may take place and a brittle iron-zinc intermetallic compound may form. Only a thin layer of thermal insulation lies between the pump body and the cable which wraps around it. Crushed insulation m not be effective. This structure is retained in Group I until these points are clarified.

The Oconee 1,2,3 coolant pumps appear to be supported on four hanger rods per pump; lateral restraint is not identified. No materials are listed. There is A-515 in the steam generator skirt flange, a Group I material, but as in other facilities a warm operating temperature could remove this consideration. The anchor bolt material is not identified either, but appears to carry substantial loads so this should be identified. Because of the extensive use of A-36, this plant could not be moved to category III but clarification of the above points could move it to Group II.

Rancho Seco 1 and Three Mile Island 1 must be retained in Group I due to a lack of information. The coolant pump is supported by the piping but is also restrained by horizontal supports attached to the pump motor. There is no information available which covers the materials and details of interest.

A-515 is used in the base flange on the skirt support of the steam generator. This is a Group I material but again might be acceptable if the minimum temperature is high enough. No mention is made of any upper horizontal restraints. If the unknown structure mentioned contains no Group I materials, and if the skirt flange is at a high enough temperature these facilities might be reclassified.

4.7.3 Pin-Column

The pin-colum structures considered in Group I were J. M. Farley 1,2, Kewaunee, Point Beach 1,2, and Prairie Island 1,2.

The J. M. Farley 1 and 2 support structure steels have been impact tested and ultrasonically inspected for through-thickness flaws and are therefore placed in material Group III. The Carpenter Custom 455 steel bolts used in the clevis attachments of the vertical columns (twelve columns, six bolts each, 1.5 in. dia., 8.5 in. long) were considered for stress corrosion cracking but were dismissed since they are under no service load except LOCA, and appear to be under no pre-stress. This should be verified.

Since Kewaunee and Prairie Island 1,2 are so similar they are treated together here. The Vascomax 300 CVM in the tie back bolts, a material susceptible to stress corrosion cracking, appears to be satisfactory here since there is no pre-tension and no stress under normal loads. Two items in the steam generator supports which are of concern in this regard are made of Vascomax 250 CVM. They are 0.5 in. dia. "Heli-Coil screws into S.G." which are under pre-tension, and 1 in. dia. "upper support ring girder wall bolts" which are stressed under normal conditions. The stress magnitudes which are carried and the specific locations of these items could not be determined from the information supplied. This is a Group I material and unless the stress states would dictate differently, these plants should remain in Group I.

Point Beach 1&2 should remain in Group I. The main columns are made of 12 in. dia. schedule 100 pipe of A-53, a material with very loose specifications. These are primary members.

4.7.4 Space Frame

Four space frame structures were considered in more detail. They are at Indian Point 2,3, Salem 1&2, and Yankee Rowe.

The reply to the NRC request from Indian Point was received too late for detailed review. Drawings were available, however, and enough information was derived from them to rate it in Group I. There is extensive use of A-53 pipe used in the columns. These columns are part of a fairly large structure so the minimum temperature may not be elevated above room temperature.

Salem 1&2 belong in Group III in spite of the materials used. The Vascomax 300 "R. C. pump hold down bolts" were considered for stress corrosion cracking but can be dismissed since they are neither pre-tensioned nor under stress under normal service loads.

Yankee Rowe is retained in Group I based on the materials used and based on some question about the minimum temperature of 200°F claimed for the support structures. The reactor coolant pump appears to be supported on three hanger rods as well as the piping, but there are no drawings giving the details or materials. Materials and drawings for the upper part of the steam generator support structure were also not supplied. Until more information is available, this facility must remain in Group I.

4.7.5 Miscellaneous Structures

Four miscellaneous structures were initially placed in Group I. They are Ft. Calhoun 1, St. Lucie 1 and Surry 1 and 2.

Ft. Calhoun was placed in Group I due to the presence of A-307 nuts and bolts. This material is widely variable and not extensively tested.

St. Lucie 1 is placed in Group I because of the presence of A-515 on the coolant pump snubber clevises. Additionally, the steam generator base casting is made of A-27 without indication of heat treatment. However, if the base is normalized or quenched and tempered this latter problem can be dismissed.

Verification of adequately high temperatures at these components would allow reclassification of this plant.

There are many reasons why Surry 1 and 2 are in Group I. First there is some concern about brittle fracture in some members. There are A-106 pipes, A-285 plates, and A-105 pipe end forgings which are all loosely specified and not tested. There are pins and adjusting bolts of 1018 steel cold drawn to 70 ksi yield point in the "horizontal support legs" which separate the coolant pump and steam generator. There are many bolts and clevis end forgings and rods of Vascomax 300 and 350. Stress corrosion cracking is the concern especially in the Vascomax 300 and 350. These are located throughout the steam generator support structure. Specific locations of concern in the coolant pump support are clevis ends and pins in the four "upper legs" with monoball assemblies which support the weight of the pump and motor (see Figure E10 through E14 in Appendix E).

4.8 Summary of Plant Ratings

The materials used in support structures were rated in one of three groups based mainly on NDT considerations, qualitatively a K_{Id} measure. In some cases where NDT data were not available Charpy V-notch or dynamic tear test data were used. For some of the materials no test data were found either from plant responses to the NRC questionnaire or from the literature. These materials were then grouped with similar materials for which data were available. The groupings were based on microstructural strengthening mechanisms. This rating of structural steels was then used as the basis for an initial rating of plants according to the materials used.

Weld metal was considered as a separate topic apart from structural steels. Most plants had a CVN requirement on the weld material as per AWS specifications. In some AWS specifications there are no test requirements but only one plant was downrated because of this uncertainty (from Group III to Group II).

The operating temperature of the support structures in the various plants is an important consideration in this study. For some plants the minimum operating temperature at specific locations could be determined more accurately and the plant placed in a lower susceptibility group as a result. This is particularly true of the plants with skirt-supported structures.

The preliminary plant ratings of section 4.6 and the above considerations were used to arrive at the final plant ratings. These are listed in Table 4.8.

Table 4.8
Final Assessment of Plant Brittle Fracture Susceptibility Groups

Group I

Millstone 2	J. M. Farley 1 & 2
Palisades	Kewaunee
Crystal River 3	Point Beach 1 & 2
Davis-Besse 1	Prarie Island 1 & 2
Rancho Seco 1	Indian Point 2,3
Three Mile Island 1	Yankee Rowe
Surry 1,2	Ft. Calhoun
Maine Yankee	St. Lucie 1

Group II

Beaver Valley 1	H. B. Robinson 2
Oconee 1,2,3	Trojan
Calvert Cliffs 1,2	R. E. Ginna
Arkansas	Haddam Neck

Group III

D. C. Cook 1 & 2
Zion 1 & 2
Salem 1 & 2

The groupings imply a fracture toughness level of confidence for the support structures in each of the plants. Group III plants are considered to be as good as careful, reasonable engineering practice can produce.

The other two groups are not meant to rate a plant as definitely high susceptibility but rather to indicate questionable areas. This is due principally to uncertainties in materials, temperatures, and in some cases lack of design details in the response to the NRC questionnaire.

The Group I plants should be given further attention. A temperature determination, inspection, or material sampling program or a combination of these should be considered as a means of removing these from the Group I category. The Group II plants are intermediate between the other two groups, neither as good as the Group III plants nor deserving the further review of the Group I plants. The NDT for materials in these plants is below the minimum operating temperature but not by a large margin. A course of action on these plants should be decided based on the experience gained in subsequent study of the plants in Group I.

4.9 Critical Flaw Sizes

The concepts of linear elastic fracture mechanics are applied in this section in order to establish the critical flaw size range in these structures. An inspection program (if instituted) would then search for cracks in this range. Since a particular geometry, material, and crack location are required to perform a stress analysis, several are chosen here.

Geometries which will be used in the following can be considered representative, but only in a general sense. The use of reasonable loadings and reasonable estimates of fracture toughness will be used to estimate hopefully realistic critical crack sizes. Since this assessment is parametric, its results can be applied to any material by varying the parameters used. In particular, the results will apply to all three plant groupings merely by choosing the appropriate K parameter.

The parameters which will be input are σ/σ_{ys} and three values of K; 35 ksi $\sqrt{in}$, 50 ksi $\sqrt{in}$, and 100 ksi $\sqrt{in}$.

σ is the gross section stress applied in tension or the outer fiber stress in bending (if both are applied simultaneously, they will be noted σ_t or σ_b, respectively), and σ_{ys} is the static yield strength of the material.

The three values of K correspond to estimates of high, medium, and low susceptibility materials, respectively.

Values of σ/σ_{ys} of interest were chosen as 0.33, 0.67, and 1.0. These are somewhat arbitrarily chosen to indicate the variation of flaw size upon the applied stress. The maximum value of 1.0 was chosen to simulate the worst design condition for these structures. Although this would seem to violate the limit of $\sigma/\sigma_{ys} < 0.8$ for (LEFM) calculations, it is partially compensated by the increase of yield stress under dynamic loading, which these calculations are meant to simulate. Any difference in the stress intensity calculations due to dynamic loading is neglected.

It is realized that under LOCA conditions the dynamic fracture toughness and dynamic yield stress apply only to the initial loading. After the initial transient the rates will probably be low enough that the static values will apply. To apply fracture mechanics at greater than yield is a more complicated proposition, and is probably less important to this assessment, because if greater than yield stress levels can be reached, large amounts of plasticity must be present, and any problem of brittle failure is mitigated. To arrive at σ/σ_{ys}, σ_{ys} must be specified also. In line with the generic nature of this section, values of 30, 36, 42, and 50 ksi to represent plain carbon, C-Mn, HSLA and low alloy steels, respectively, will be used.

The geometries chosen include the center-cracked wide plate in tension, the edge-cracked tension member of finite width, the flange-cracked I-beam in bending, the shear pin, the toe crack of a fillet weld in a reinforced plate under tension, and the finite surface crack in a semi-infinite plate. Specific dimensions will be mentioned in each example.

4.9.1 Center-Cracked Wide Plate (Ref. 4.15)

This example (Fig. 4.1) is most applicable to the skirt supported structure, however, it is difficult to envision how a through-thickness flaw could originate in the middle of these plates in the orientation perpendicular to the tensile direction. About the only conceivable scenario would be that a crack forms while gas cutting to shape, followed by welding the gas cut edge to another plate. The reason for its inclusion is its easy calculation, and the applicability of this data to the following cases.

4.9.2 Edge-Cracked Tension Member of Finite Width (Ref. 4.15)

This geometry (Fig. 4.2) is thought representative of two separate cases. One is the presence of a circumferential defect in a pipe (the ASTM allows up to 12.5% penetration in some cases), assuming that the diameter of the pipe is large enough not to affect the solution; and the second is a lack of fusion, or perhaps a heat-affected zone crack in two butt-welded tension members. Assuming that the thickness of material is 2" (representative of both the thickest pipe encountered, and many heavy beams), 12.5% of 2" is about 1/4". This would also be similar to the size of a weld bead in a multipass butt weld. In both of these cases a/b = 0.12. In the equation $K_I = \sigma \sqrt{\pi a} F(a/b)$, the factor F(0.12) = 1.25. This implies that a constant multiplicative factor (equal to F^2) of 1.56 should be divided into the crack sizes resulting from the previous section under given conditions of stress and fracture toughness.

At yield stress levels of 30, 36, 42, and 50 ksi, this implies that the critical half-crack dimension (bearing in mind that a/b is held constant, not material thickness) is 0.28, 0.19, 0.14 and 0.10 in., respectively for K_{Id} = 35 ksi $\sqrt{in}$. 0.56, 0.39, 0.29 and 0.21 in. for K_{Id} = 50 ksi $\sqrt{in}$. and 2.27, 1.58, 1.15 and 0.81 in. for K_{Id} = 100 ksi $\sqrt{in}$.

The values calculated for K_{Id} = 100 ksi $\sqrt{in}$ are not really useful because they refer to much thicker sections. If instead b is held constant (at 2") and is again held at 30, 36, 42, and 50 ksi, the following a_{crit} results

K_{Id} (ksi$\sqrt{in}$) \ σ(ksi)	30	36	42	50
35	.28"	.21"	.16"	.12"
50	.44"	.35"	.29"	.22"
100	.80"	.70"	.62"	.53"

4.9.3 Flange-Cracked I-Beam in Bending (Ref. 4.17)

This geometry (Fig. 4.3) is similar to the previous except that an I-beam section is used with section dimensions 8" wide by 1-1/2" thick flanges and a 1'5" x 5/8" thick web. Assuming that loading occurs to stress the outer fibers, the same equation as used in the previous example applies with a different functional dependence of F(a/b), where b is the flange thickness. This case is less severe than the edge-cracked plate in tension, F(.125) = 1.2, and F^2 = 1.44. Thus the cracks allowable are about 10% larger than the previous case. At higher values of a/b, this case is much less severe, for example at a/b = .3, then F^2 = 1.89 compared with 2.62 in the previous geometry.

A comparison of the relative functional dependences of F(a/b) for the two cases is shown in Fig. 4.3b.

4.9.4 Shear Pin

This geometry simulates a clevis shear pin (a relatively common geometry in all the structures, especially for snubber attachments and other lateral restraints) or the main load-bearing members in pin-column structures. It is a two-dimensional approximation to a cylindrical geometry, and is probably more conservative because of this, due to added restraint. Figure 4.4 illustrates the geometry, and reasonable choices of a and b of .030" and 1.75" ("a" corresponding to some local surface decarburization perhaps), leads to a/b of 0.02. This implies that $K_{II}/Q/b$, is 3.2. Assuming the yield strength in shear is 1/2 that in tension, for a unit width of 3.5" deep material: $Q = \frac{\sigma_{ys}}{2} \times 1 \times 3.5 = \frac{3.5}{2} \sigma_{ys}$ lbs. Letting σ_{ys} = 150,000 and 330,000 psi (simulating shear pins of hardened material) this results in Q/b = 150,000 and 330,000. With a/b = .02 this implies a necessary toughness (see Fig. 4.4b) of 3.2 x σ_{ys} ksi $\sqrt{in}$., which is not attainable in these high strength materials. Even if a/b = .001 a toughness of 2/3 σ_{ys} ksi $\sqrt{in}$. is necessary, which is probably possible for a good 150 ksi yield material, but not for a 330 ksi yield material. These K's are K_{IIc}, but evidence indicates that $K_{IIc} \sim K_{Ic}$ (Ref. 4.18, 4.19). Such materials apparently deserve close scrutiny. If the loads are reduced to about half of yield, the toughness requirement is half also, but the ultra-high strength steel would still have trouble meeting a necessary K_{IIc} of 100 ksi $\sqrt{in}$.

4.9.5 Toe-Crack in Reinforced Plate Under Tension

This situation applies to a cover-plated tension flange, such as an I-beam (see Fig. 4.5). An appropriate value of "a" would again be ~ 1/4" (see previous sections on tension members). Such a situation yields $K_{Ic}/\sigma = 1.11$. For $K_{Ic} = 35$ ksi $\sqrt{in.}$, this implies that $\sigma = 31.5$ ksi is the critical condition. If, alternatively σ = 36 ksi, and $K_{Ic} = 50$ ksi $\sqrt{in.}$, a critical crack length of 0.35" results. For $\sigma = 36$ ksi, and $K_{Ic} = 35$ ksi $\sqrt{in.}$, a critical crack length of .2" results. To provide a critical crack depth of 0.5" requires a K_{Ic}/σ ratio of 1.85.

4.9.6 Finite Size Surface Crack (Ref. 4.20)

Up to this point, all flaws considered have been mathematically treated as infinite in one dimension. It is the intention of this section to quantify how conservative this assumption is compared to the case where all dimensions of the crack are finite. This will be done by comparing the case of the edge-cracked tension member of finite width (Fig. 4.2) with the same geometry where the length of the crack is not infinite, as treated in Section XI of the ASME B & PV code (Fig. 4.6).

Picking a material depth of 2" and a crack depth of 1/4", existing in materials with fracture toughness of 35, 50, and 100 ksi $\sqrt{in.}$, the applied stress for crack initiation is 32,300 psi, 46,200 psi, and 92,400 psi, respectively, for the non-finite treatment.

In order to calculate σ_m for the finite crack, the equation used is

$$K_I = \sigma_m M_m \sqrt{\pi a/Q} + \sigma_b M_b \sqrt{\pi a/Q}$$

where m and b refer to membrane and bending stresses. In this case, no bending is present, and the second term in the right hand side of the equation drops out. In order to determine Q, the aspect ratio of the crack must be known. We shall assume values of a/l = 0.1 (a 10:1 length to depth ratio), and 0.5 (a 2:1 length to depth ratio). Additionally the ratio of σ to σ_{ys} must be known.

M_m can be obtained from Fig. 4.7 directly at this stage; and the above equation rearranged as

$$\sigma = \frac{K_I}{M_m \sqrt{\pi a}} \sqrt{Q} = A \sqrt{Q}$$

where the appropriate values of A found in the following table should be used.

K_I = (ksi$\sqrt{in.}$)	35	50	100
a/l = 0.1	34,600	51,300	103,000
M_m = 1.14			
a/l = 0.5	35,900	51,300	103,000
M_m = 1.10			

values of Q (see Fig. 4.8) for σ/σ_{ys} = .5, .8 and 1.0 are

σ/σ_{ys}	.5	.8	1.0
a/l			
0.1	.91	.99	1.06
0.5	2.24	2.31	2.40

values of $A\sqrt{Q}$ = (in psi) are:

a/l \ σ/σ_{ys}	0.5	0.8	1.0	
0.1	33,000	34,500	35,700	for K = 35 ksi $\sqrt{in.}$
0.5	53,700	54,600	55,600	
0.1	47,200	49,200	50,900	for K = 50 ksi $\sqrt{in.}$
0.5	76,800	77,900	79,500	
0.1	94,400	98,500	101,900	for K = 100 ksi $\sqrt{in.}$
0.5	153,500	155,900	158,900	

Depending upon the value of σ_{ys}, the new critical stress for a 10:1 crack ranges from 33,000 psi to 35,700 if K = 35 ksi $\sqrt{in.}$ compared to 32,300 for the non-finite crack. For the 2:1 crack the range is from 53,700 to 55,600 psi; a significant difference becomes evident as a/l increases.

The comparison of allowable stress is most easily made if one realizes the infinite crack corresponds to a/l = 0 and includes the values previously noted in the following table.

K = 35 ksi $\sqrt{in.}$

a/l \ σ/σ_{ys}	0.5	0.8	1.0
0.0		32,400	
0.1	33,000	34,500	35,700
0.5	53,700	54,600	55,600

$K = 50$ ksi $\sqrt{in.}$

a/l \ σ/σ_{ys}	.5	.8	1.0
0.0		46,210	
0.1	47,200	49,200	50,900
0.5	76,800	77,900	79,500

$K = 100$ ksi $\sqrt{in.}$

a/l \ σ/σ_{ys}	.5	.8	1.0
0.0		92.420	
0.1	94,400	98,500	101,600
0.5	153,500	155,700	158,900

One can see that the allowable stresses calculated for the finite geometry crack increase substantially as a/l increases for constant "a".

The third column ($\sigma/\sigma_{ys} = 1.0$) is the most interesting, as it indicates the maximum yield strength a material of a given fracture toughness can utilize as a function of crack aspect ratio.

Going back to our present example, if a infinite through thickness crack of a/b = 0.125 (with a = .250 and b = 2") becomes critical at a stress level of 32,300 psi in a 35 ksi $\sqrt{in.}$ material, the equivalent 2 to 1 aspect ratio (length/depth) crack that will go critical at this stress level has a/l = .32 and is 0.64" deep, and of course 1.28" long.

What are the implications of this section? If one can apply the effect of aspect ratio to other geometries and obtain similar increases in crack depth, the possibility exists that even the Group I structures may be considered safe. This aspect ratio argument may not be easily applic ble to all geometries, however, and in some (the high strength shear pin, for example) would still not provide an acceptable condition. Finally, there do exist defects that would be expected to take a geometry which would be similar to the non-finite width (very high a/l aspect ratio) and for which this argument simply does not apply. One such defect which is expected to be relatively common is lamellar tearing (see Section 5). Whether or not lamellar tearing is produced by a ductile tearing process, it introduces sharp cracks into a structure. If the combination of stress and fracture toughness is appropriate, these cracks may propagate.

The critical defect sizes for the various types of geometry, K_{Ic}, and loading level are tabulated on the following page (Table 4.9). Reviewing this tabulation, and keeping in perspective the critical defect size of the shear pin case (when made of ultra high strength steel), there are some categories of cracks where adequate assurance against brittle fracture is met, and others where it is questionable at best.

Table 4.9
Tabulation of Critical Flaw Sizes

K_{Id} (ksi$\sqrt{in}$)	σ(ksi)	Critical Defect Size (in)
Center cracked wide plate		
35	30	.86
	36	.60
	42	.44
	50	.32
50	30	1.76
	36	1.22
	42	.90
	50	.64
Edge cracked tension member of finite width (= 2")		
35	30	.28
	36	.21
	42	.16
	50	.12
50	30	.44
	36	.35
	42	.29
	50	.22

Flange-cracked I-beam in bending

Critical defects are approximately 10% larger than previous case, assuming $\sigma_m = \sigma_b$ and $b_{flange} = b_{plate}$

Shear pin (3.5" diameter) approximation

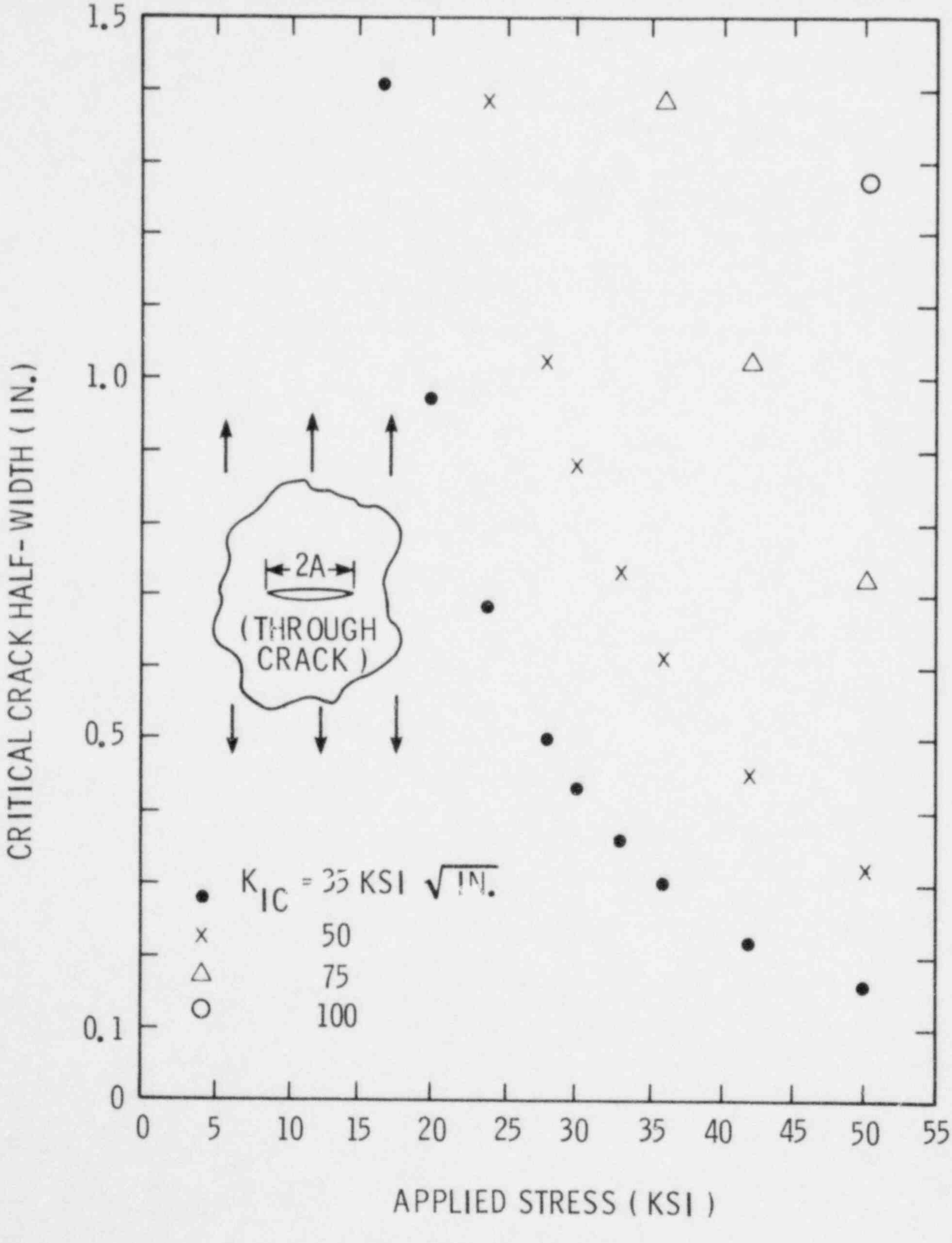
σ_{ys} x 3.2	$\sigma_{ys}/2 = \sigma_{ys}$	.035"
σ_{ys} x .67	$\sigma_{ys}/2 = \sigma_{ys}$	.00175"
$\frac{\sigma_{ys}}{3}$	$\frac{\tau_{ys}}{2}$	.00175"

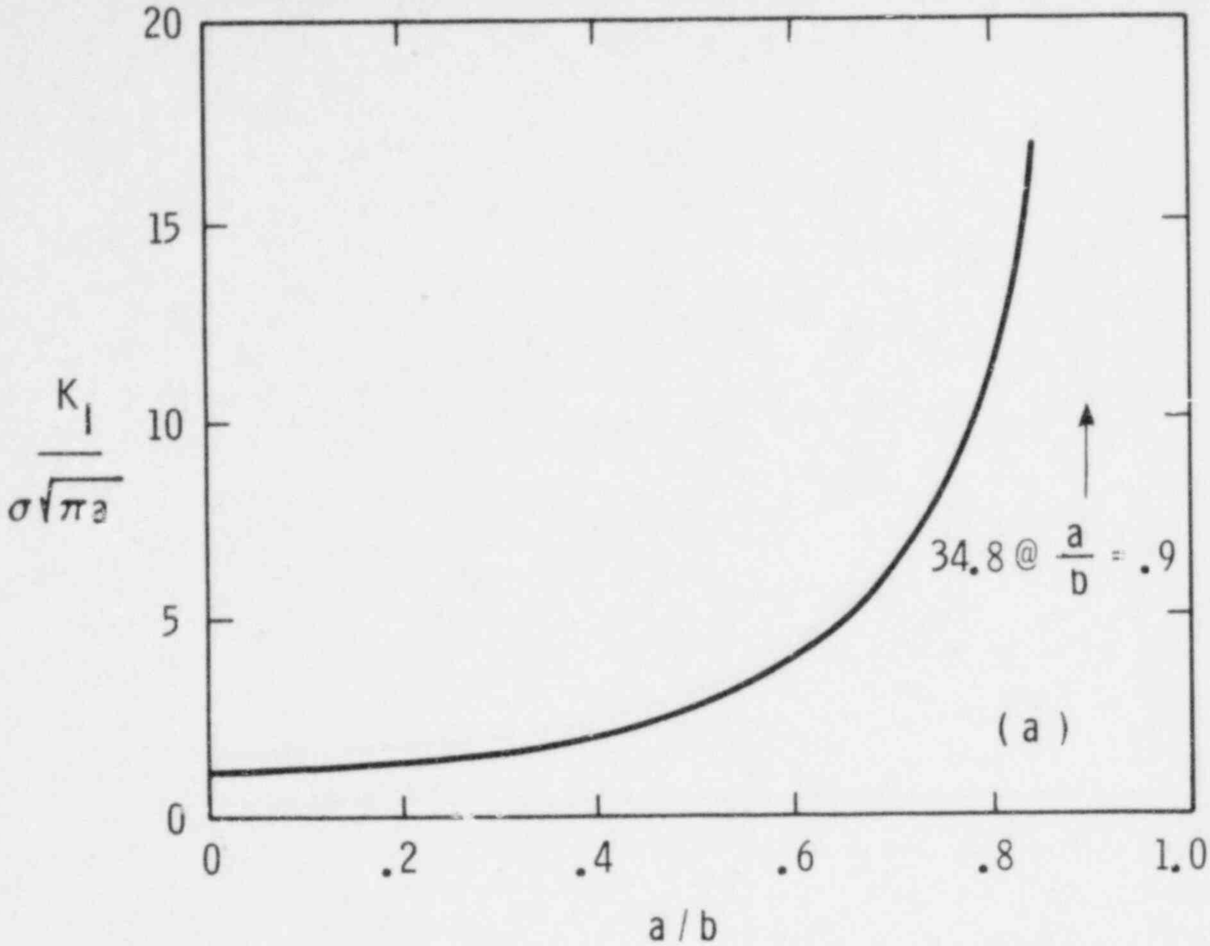
110 ksi $\sqrt{in.}$ for 330 yield maraging steel
50 ksi $\sqrt{in.}$ for low alloy steel heat treated to 150 ksi yield

Table 4.9 (cont'd)

K_{Id} (ksi $\sqrt{in}$)	σ(ksi)	Defect Size (in)
Toe crack at reinforced plate under tension (2" to 4" section transition)		
35	31.5	.25
	36	.20
50	36	.35
1.85	σ	.5
Finite surface crack in tension member of finite width (= 2")		
		depth x length
35	56	.25 x .5
	36	.25 x 2.5
50	79	.25 x .5
	51	.25 x 2.5

FIG. 4.1 CENTER -CRACKED WIDE PLATE IN TENSION





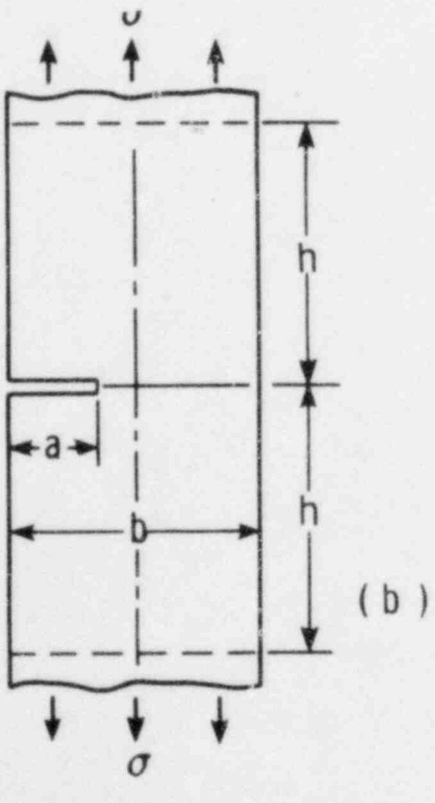


FIG. 4.2 EDGE-CRACKED TENSION MEMBER OF FINITE WIDTH. (a) STRESS INTENSITY, (b) GEOMETRY

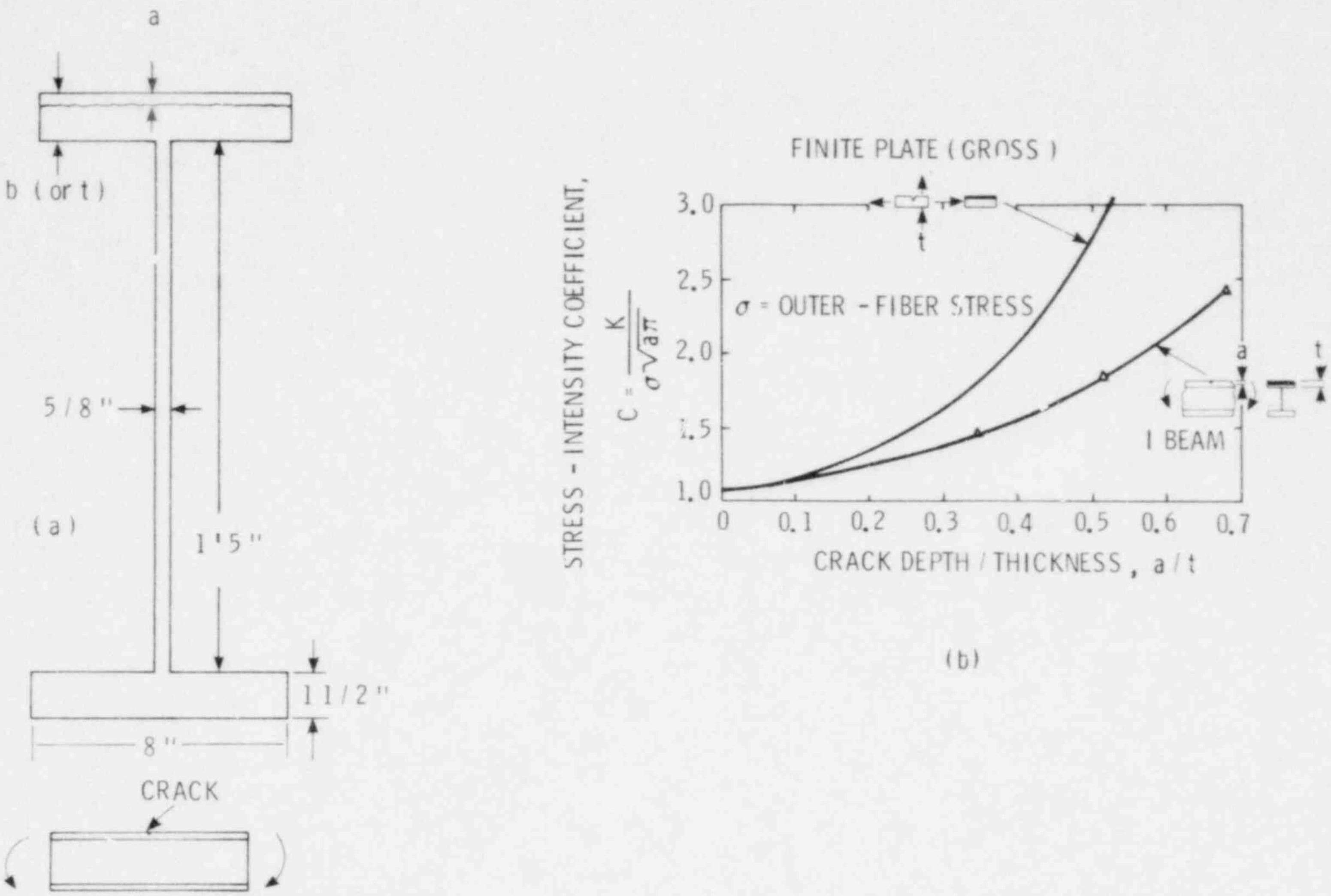


FIG. 4.3 - FLANGE - CRACKED I - BEAM IN BENDING (a) GEOMETRY, (b) STRESS INTENSITY

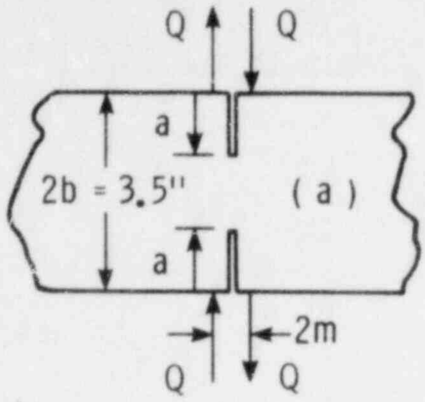
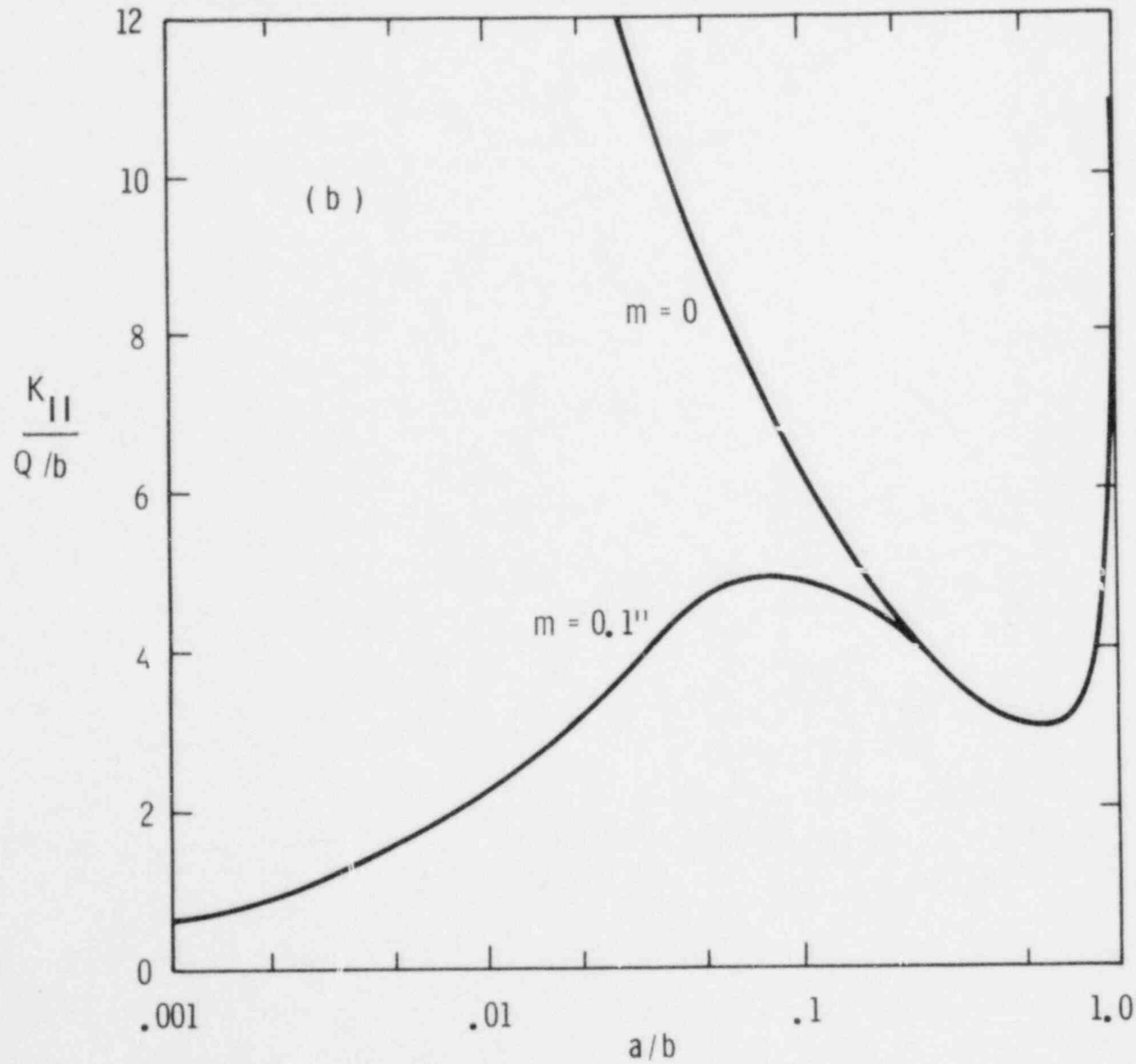
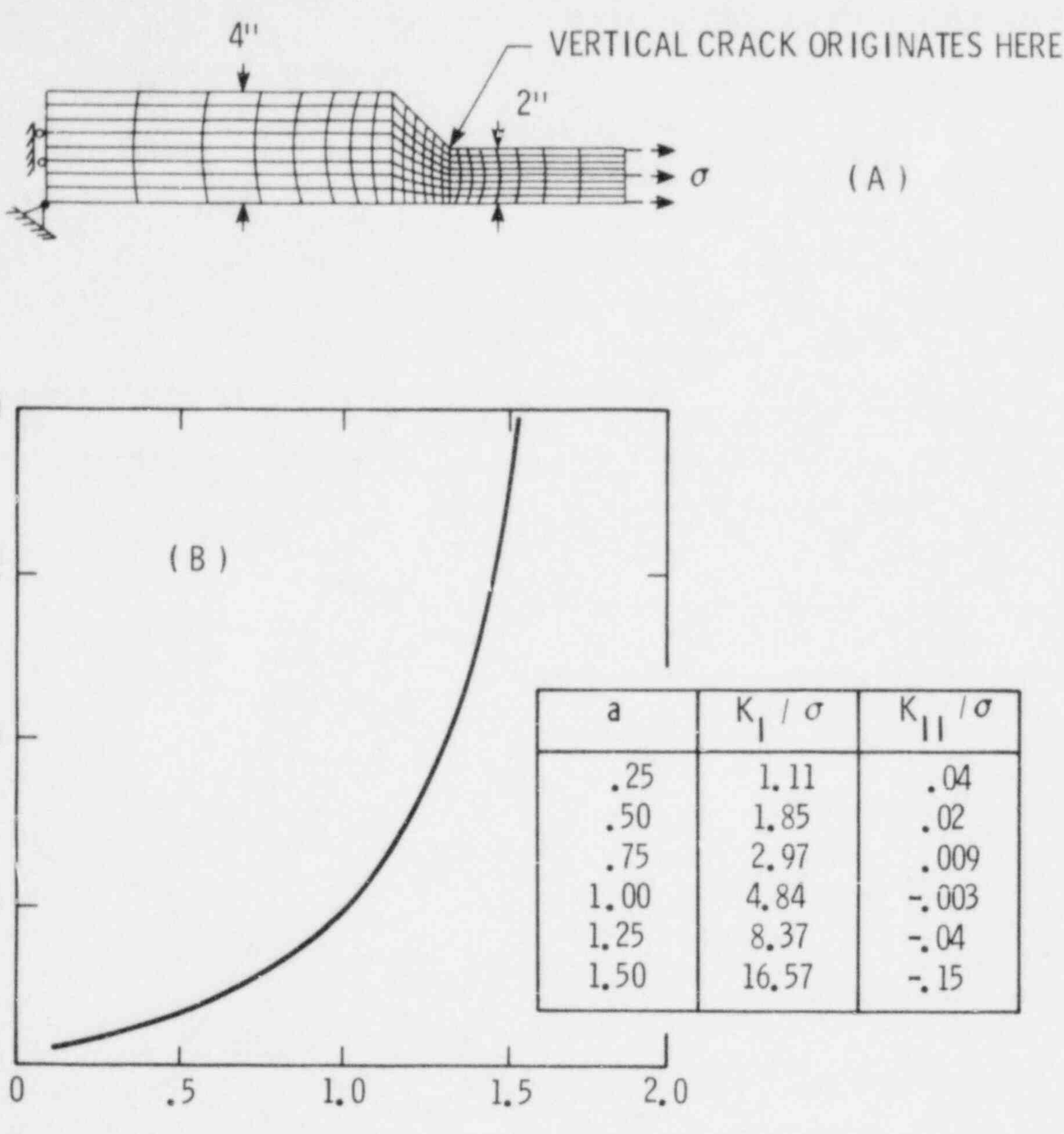


FIG. 4.4 SHEAR PIN
(a) GEOMETRY,
(b) STRESS INTENSITY





a	K_I / σ	K_{II} / σ
.25	1.11	.04
.50	1.85	.02
.75	2.97	.009
1.00	4.84	-.003
1.25	8.37	-.04
1.50	16.57	-.15

FIG. 4.5 CRACK AT THE TOE OF A FILLET WELD IN A REINFORCED PLATE UNDER TENSION (A) GEOMETRY, (B) STRESS INTENSITY

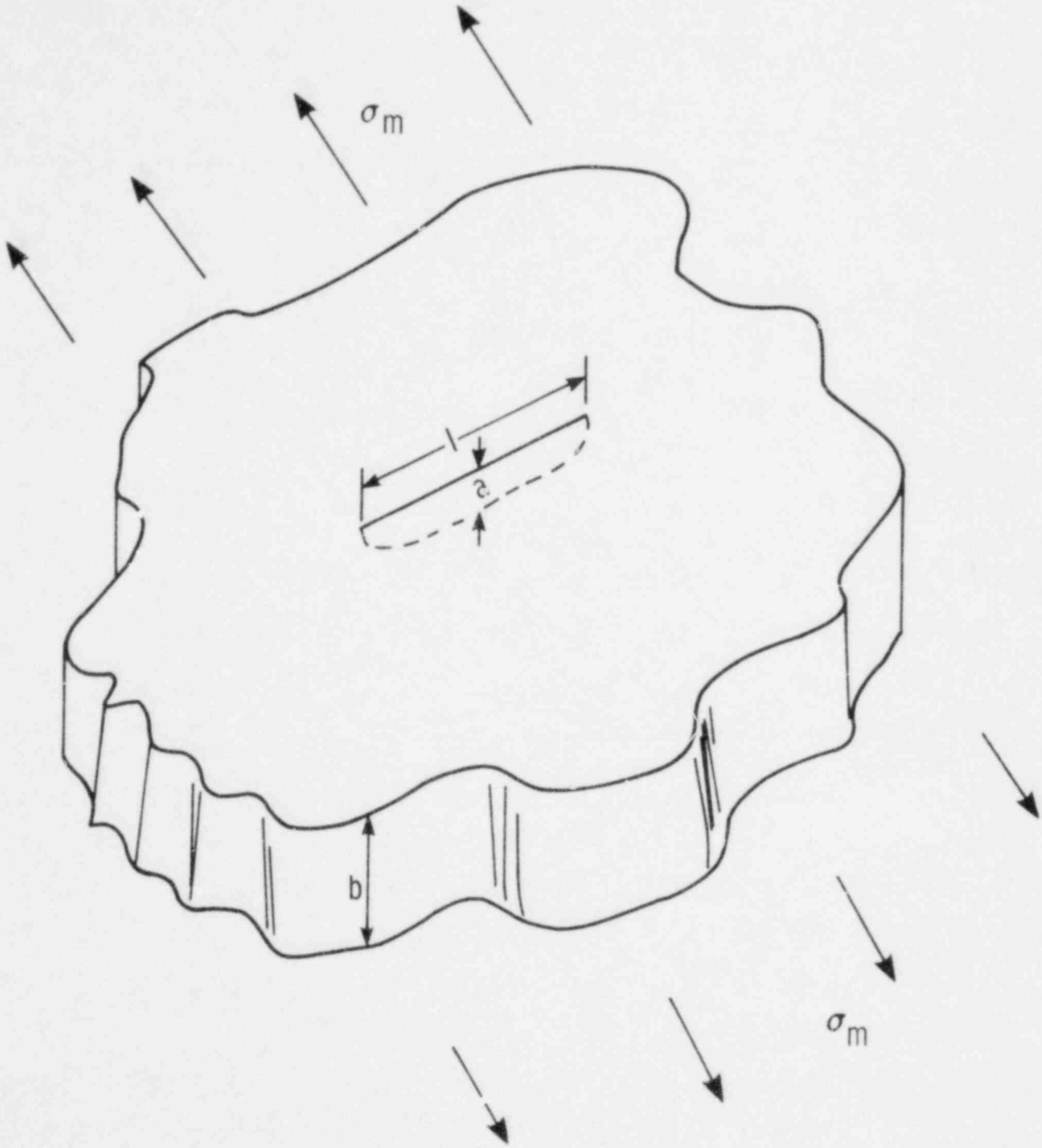


FIG. 4.6 GEOMETRY OF FINITE SIZE SURFACE CRACK

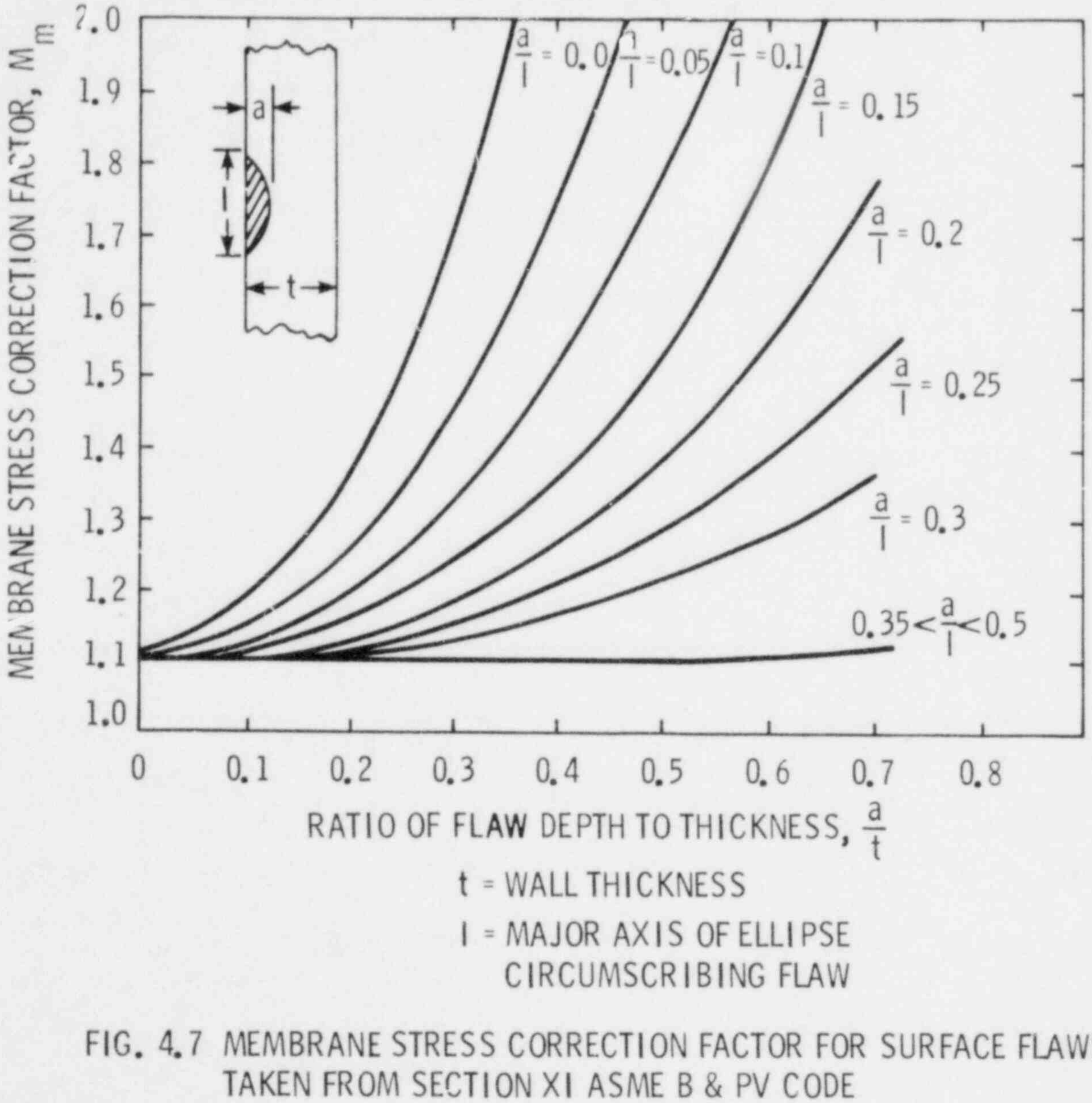


FIG. 4.7 MEMBRANE STRESS CORRECTION FACTOR FOR SURFACE FLAWS, TAKEN FROM SECTION XI ASME B & PV CODE

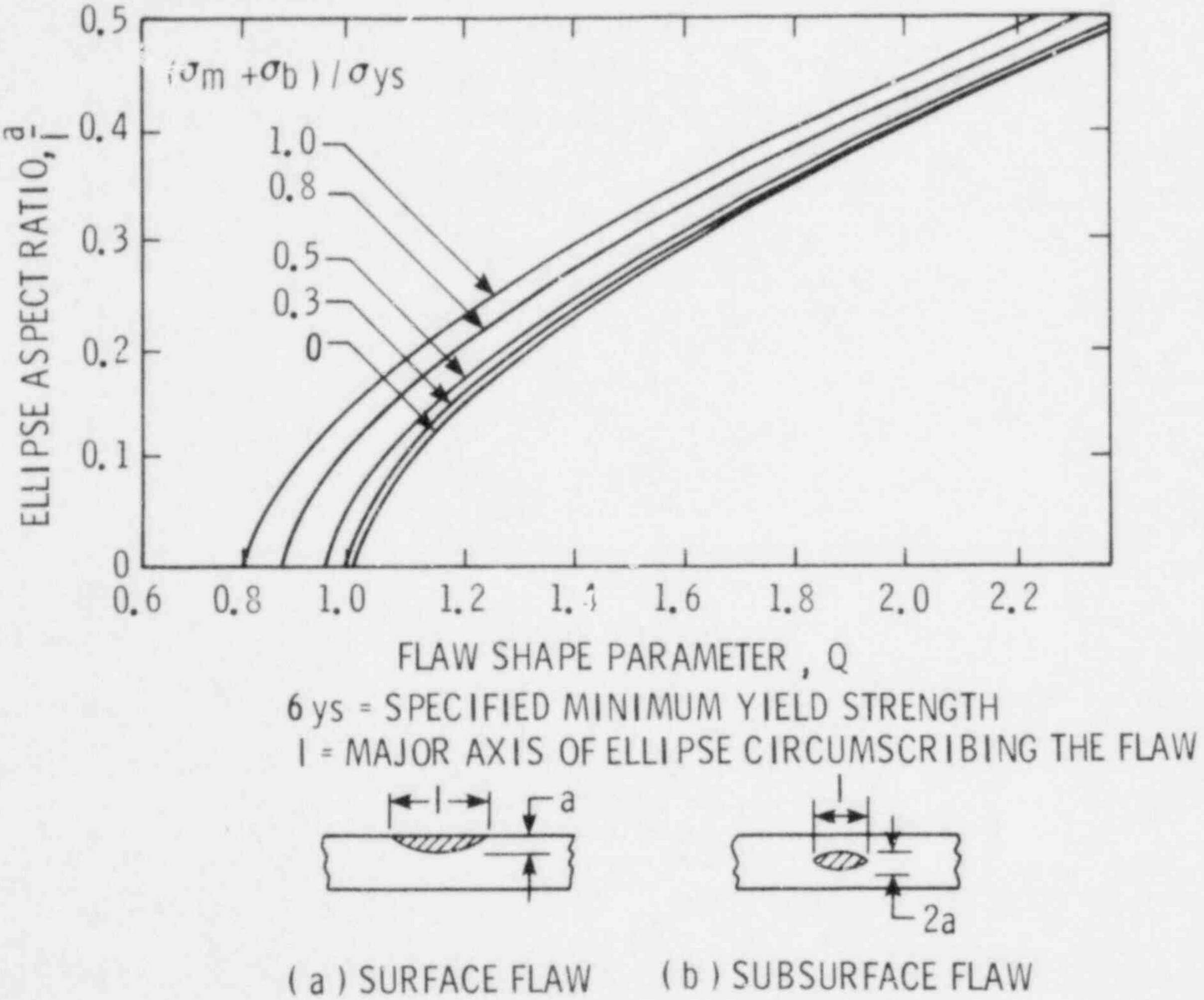


FIG. 4.8 FLAW SHAPE PARAMETER TAKEN FROM SECTION XI ASME B & PV CODE

5.0 Lamellar Tearing

5.1 Definition

A useful definition of lamellar tearing is contained in the following paragraph taken from Reference 5.1.

> Lamellar tearing, a form of cracking occurring in planes essentially parallel to the rolled surface of a plate under high through-thickness loading tends to initiate by the decoherence or cracking of elongated inclusions. Voids form which grow and link together by the plastic tearing of the intervening matrix, along the horizontal and the vertical planes, producing a characteristic step-like appearance to the fracture. Though welding is not a necessary condition, lamellar tearing has been generally associated with welded joints and occurs in the base metal with insufficient short-transverse ductility when subjected to high through-thickness strains generated if weld thermal contraction is inhibited by structural restraint.

Figure 5.1 (Ref. 5.2) is a diagram of a partially developed lamellar tear, showing the essential features, and Fig. 5.2 shows the completed tear. Not shown here is the proximity of the weld material and heat affected zone (HAZ) when the tearing is associated with welding, considered here to be the only cause. The tearing almost always lies in the parent material, often outside the transformed or visible HAZ and generally parallel to the weld fusion boundary.

Lamellar tearing has been reported (Ref 5.3), to be an elevated temperature phenomenon occurring in the temperature range 200-300°C. However, in a later series of tests on six steels of various thicknesses (Ref. 5.4), it was found that all lamellar tears (except one at 100°C) occurred at room temperature up to 75 minutes after completion of the weld. In Reference 5.5 it states that "tearing has been observed to occur even days after completion of welding".

More complete discussions of the lamellar tearing process and its causes and particularly the metallurgical preventative measures are covered in the literature and will not be repeated here. A single reference article with an excellent overview was prepared by Porter (Ref 5.6). An annotated bibliography at the end of the references in Section 5 is included to help guide a reader interested in pursuing this topic.

5.2 History

Lamellar tearing has probably occurred for as long as welded structural steel construction has been used, and it "has been recognized by knowledgeable designers and welding engineers for over 30 years (particularly in the design of pressure vessels)" (Ref. 5.6). However, the first paper describing this type of defect appeared as late as 1956 (Ref. 5.7). This would be unusual except that lamellar tearing usually is a subsurface defect, and is most common in thick material[1], both effects making it difficult to detect. It has recently been detected more frequently in structures due to increased use of ultrasonic techniques. The literature reflects this with roughly 50 papers now appearing per year (Ref. 5.7).

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[1] However, "... it has been mistakenly presumed that lamellar tearing is only a problem in thick material." "... it can also occur in thin material..." (Ref. 5.16) if the restraint conditions or weld size is large enough.

Lamellar tearing has been observed in virtually every type of welded structure with particular emphasis in the offshore oil drilling platform construction industry. From the literature in this area, it would be expected to be a relatively common defect. But in spite of this there have been virtually no documented in-service failures[1] which could be traced to lamellar tearing. A single exception was reported in Reference 5.7 where a lamellar torn mounting plate in the wheel assembly of a large trailer failed while braking and "... turned over, burying a private car containing two persons." This relatively rare failure history could be a result of design safety factors used, the infrequent application of extreme loads for which large structures are designed, redistribution of stresses in these usually redundant and ductile structures, the relatively good inspection of material, welds, and completed structures before service, or a combination of all these reasons.

Recent interest in lamellar tearing has been directed at finding materials, developing welding and annealing techniques, changing design practices, and improving inspection procedures and techniques to minimize the tearing problem. Current studies of lamellar tearing are primarily aimed at new structures but can also be useful in this program of assessing the adequacy of existing structures. Lamellar tearing is of particular interest in steam generator support structures and

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[1] Note that failures during fabrication and erection are not included here. These are excluded since substandard welds might be detected up to final acceptance inspection and incidental loadings during fabrication can sometimes exceed the service design loads.

primary coolant pump support structures because of the problems at North Anna Units 1 and 2. In Reference 5.8, parts 5b and 5c it was stated that "the materials from which the supports were fabricated are inherently susceptible to brittle fracture" and "the materials and design of the supports render them especially susceptible to lamellar tearing."

5.3 General Discussion

Lamellar tearing is an emerging topic and an effort is being made to establish how to prevent its occurrence. However, there are still some very basic questions which have not been answered. In particular, the seriousness of the problem is not well quantified. At the present time if any lamellar tearing damage is found it is considered to be intolerable and thus is repaired. This attitude is a natural response in a situation in which there is no information. Studies are needed which would indicate residual strength of lamellar torn joints.

Another emerging topic is the study of ductile fracture. This is mentioned here because it is closely related to lamellar tearing. The link between the two topics is perhaps best illustrated in Reference 5.9 where the failure mode of a notched tensile specimen is shown. The specimen was cut from a rolled member with the specimen axis in the ST direction and displays a failure mode identical to that seen in lamellar tearing. Voids are noted to initiate at impurity sites, grow and link into planar assemblages, and subsequently become joined by shear failure perpendicular to these planes. A schematic figure in Reference 5.9, is identical to lamellar tearing schematics, e.g., Fig. 5.2. High hydrostatic tensile stresses combine with large plastic strains to produce void growth and the results shown. The topic of Reference 5.9 is a presentation of a model to explain the observed physics. The point in mentioning this is that good analytical studies which predict the onset of lamellar tearing appear to be predicated on the formulation of good ductile fracture models. This is probably one to three years from being a computational reality.

Enough analytical work has been done (Ref. 5.10) to verify that a hydrostatic tensile zone should exist beneath the welds in a T-joint. But void initiation and subsequent tearing cannot be modeled. Thus lamellar tearing studies for the near future should probably be principally experimental studies with a minimal amount of computational aid.

A point which should be made here is that prevention of lamellar tearing in steam generator and reactor coolant pump supports means designing such that large plastic tensile strains in the ST direction accompanied by hydrostatic tensile stress in rolled steel members does not occur. If these conditions cannot be prevented then either a very ductile, low yield strength weld metal must be used or the parent metal must be a lamellar tear resistant material.

This section began with the observation that the seriousness of the lamellar tearing problem is not known. The recommendation was made that further studies are necessary and these must be mainly experimental. This serves as a prelude to the approach taken here to a possible lamellar tearing situation in steam generator and reactor coolant pump support structures.

In the following sections, factors in the literature which have been noted to affect lamellar tearing susceptibility are listed. Based on these factors an attempt is made to locate all joints in sample structures which might be expected to show lamellar tearing.

5.4 Susceptible Structures

Some structural designs, welding details and procedures, and materials are more susceptible to lamellar tearing than others. And there are few distinct combinations which would enable classification of a structure as unacceptable. Consequently, a classification based upon all known factors affecting susceptibility to lamellar tearing will be established. Each factor will be listed and discussed in turn. The factors to be evaluated are: parent material, plate thickness, weld bead geometry, electrode material, joint geometry, material testing, welding process, stress relief, and post weld inspection, restraint during welding, and service loading.

5.4.1 Parent Material

The parent material type is very important in minimizing lamellar tearing. But the ranking of the susceptibility of various material types is not generally agreed upon. For example in Reference 5.1 the susceptibility of 14 steels was tested using the Lehigh lamellar tearing test method and the following was stated:

> "Investigation of lamellar tearing susceptibility on a wide range of materials has shown that susceptibility to tearing is a function of many variables and cannot be generalized on the basis of steel grade, plate thickness, deoxidation practice, etc."

Yet these same authors in a later publication state (Ref. 5.11) a more positive correlation:

> "The minor change in the ductility and energy* for the fully-killed steels when welded under high restraint suggests an absence of damage to these steels. For the semi-killed steel the significant drop in energy and ductility caused by the restraint during welding suggests incipient lamellar tearing and perhaps strain aging."

The above statement must be mitigated by a statement (Ref. 5.12 reporting that <u>any</u> steel can be made to exhibit lamellar tearing, even the newest steels which have been specifically formulated and processed to be resistant to lamellar tearing.

An excellent discussion of the metallurgical findings up to 1975 is given in Reference 5.6. But a more quantitative statement is contained in Reference 5.5 where a strong correlation between lamellar tearing and sulfur content was observed: "control of sulfur level is paramount in obtaining good through thickness properties. Most instances of lamellar tearing have been associated with steels of sulfur contents above about 0.02%, while levels below about 0.005-0.01% are considered necessary to insure optimum performance."

In summary, semi-killed steels with a sulfur content above 0.01% will be considered to be susceptible and fully killed steels with a sulfur content below 0.01% will be considered less susceptible to lamellar tearing.

*The lamellar tearing test used allows deformation of the joint while under load. The energy absorbed for the load required to cause failure is cited here.

5.4.2 Plate Thickness

The plate thickness is an important factor in evaluating lamellar tearing. In Reference 5.11 a study was made based on a review of the literature and visits to UK fabricators and users. The following was found: "Lamellar tearing has been reported in plate thicknesses ranging from 10 to 175 mm." (0.4 to 7.0 in.) The absence of tearing in thin plate is attributed to relief due to flexure of the relatively thin plate, but it was concluded that "there are few problems with plates below 25 mm (1 in.) in thickness." Plates with less than 0.5 in. thickness will be dismissed as nonsusceptible if there is any bending relief allowed by the joint geometry.

5.4.3 Weld-Bead Geometry

The weld bead geometry is a factor in the lamellar tearing. Large welds, for example a single-sided rather than a double sided weld on a T-joint, are slightly worse. In Reference 5.13 it is stated that "... just over half the replies (to the questionnaire) considered that there was a minimum weld size below which lamellar tearing was not a problem. Of these replies about one-quarter put the critical bead width less than 12 mm while about three-quarters felt it was 12 mm or above." This is reinforced by References 5.13 and 5.2 which consider weld bead volume. A weld bead cross-sectional area less than 0.1 sq. in. will be considered a less susceptible weld.

A full penetration weld is worse than a simple fillet weld as far as lamellar tearing is concerned, but this is difficult to quantify.

5.4.4 Electrode Material

The electrode material is important, with virtually all sources stressing that low hydrogen content is desirable or necessary since hydrogen can cause embrittlement. The use of low hydrogen electrodes does not insure a good weld or even a low hydrogen weld since the electrodes, for example, could be left out in wet environments. Using electrodes with a yield strength which is equal to or less than the parent metal is also reported by some fabricators to have eliminated lamellar tearing problems in some instances (Ref. 5.13, also mentioned in Ref. 5.4 and Ref. 5.2). Thus the difference in yield strength of the weld deposit and parent materials will be considered to be a factor. For the structures considered here this is seldom an aid since welding rod material with a yield strength lower than mild steel is not commercially available.

5.4.5 Joint Geometry

Joint geometry is perhaps the most important factor. If through thickness stresses are not produced by either the welding process or the subsequent loading then lamellar tearing must be dismissed. The literature refers to "restraint level" extensively as a qualitative (and sometimes quantitative) measure of the ST loading on the joint due to thermal strains caused by the welding process. Virtually all the references mention the reduction of ST stresses as a means of avoiding lamellar tearing and References 5.2 and 5.13 give suggestions regarding specific geometries. If the plane of the weld/base metal interface is perpendicular to the rolling plane rather than parallel to it, an acceptable joint geometry will result. This removes many welded members from consideration. Both good and bad joint geometries are illustrated in Appendix D.

5.4.6 Material Testing

Material testing is also a very important consideration. There are tests specifically designed to rank susceptibility to lamellar tearing and Reference 5.5 shows 28 different types, none of which have been applied to most of the support structures being evaluated. The short transverse tensile specimen reduction of area measurement (STRA) is perhaps the most reliable conventional method used. There seems to be no correlation with longitudinal properties or ST yield or ultimate stress levels. So only STRA will be considered to be an efficacious measure here. (See Refs. 5.5 and 5.14 for quantitative measures.)

5.4.7 Welding Process

The welding process can minimize the potential for lamellar tearing. High heat input reduces the potential for lamellar tearing by tending to partially anneal previous bead layers. Peening after each pass will also help as was quantified in Reference 5.4. Buttering, the process of laying down a base layer of weld initially, upon which to make the joint will also aid. Preheating, if properly done will aid. As mentioned in References. 5.13 and 5.2, however, these measures only reduce the potential for lamellar tearing. They cannot by themselves guarantee successful avoidance of the problem in a susceptible joint.

5.4.8 Stress Relief

Stress relief could reduce the potential for lamellar tearing if applied before the weld cools. Unfortunately this is not practical and stress relief is ordinarily only a partial aid to an already damaged joint. It cannot be considered as a prevention method and as such, post weld stress relieving is given no consideration here.

5.4.9 Post Weld Testing

Post weld inspection using ultrasonic measurements is useful. Unfortunately, this method requires good access and presents problems in interpretation. This particularly was the case several years ago when many of the structures which are under consideration here were built. Nevertheless, positive consideration is given here to plants using post weld ultrasonic inspection.

All the above factors will be used to rate the various structures.

5.5 Qualitative Selection of Joints for Further Study

Five plants, including one plant from each of each of the categories listed in Section 2.3 were selected. for the lamellar tearing susceptibility anlaysis listed above (and more comprehensively illustrated in Appendix D). In an effort to be thorough, each welded joint was identified on drawings if it required further study and assigned a joint number. Good joints were also identified to keep track of joints which had already been considered.

Included in Appendix D is a system of quantifying the qualitative analysis. That is, it is a method of order ranking joints so that one joint can be ranked more susceptible to lamellar tearing than another. The system is not used here since it was found that none of the joints analyzed by the qualitative analysis could be dismissed by the quantitative system. Joints which are dismissed would require the same inspection as bad joints so nothing is saved. The system is included and demonstrated with one plant as it may serve some other project.

Since the verbal identification of the selected joints is difficult and usually ambiguous, reproductions of blueprint sections have been used extensively and are included in Appendix E.

5.6 Qualitative Lamellar Tearing System Applied

A qualitative analysis for lamellar tearing of a selected plant in each structural category is given in the following sections.

5.6.1 Sliding Pedestal Support

The Calvert Cliffs facility is a representative sliding pedestal support structure. There are several locations which were identified as susceptible joints in the qualitative screening process. The locations are identified by hexagons numbered sequentially.

The upper support key bracket on the steam generator (two brackets per generator) is an all welded unit which has four locations of concern as identified in Fig. E1. The reactor coolant pump has several joints which are examined also. Figures E2 through E4 show these joints. Since these joints are also presented as an example in Appendix D they will not be discussed further here.

The lower support for the steam generator and a major part of the upper support are embedded in concrete (the boundary line for this study) so they are not considered. The horizontal snubbers and associated clevis ends are vendor-supplied items with no details furnished to allow for evaluation. This plant should be given further attention at the joints mentioned above.

5.6.2 Pin-Column

Prairie Island is the representative pin-column structure. The steam generator support is shown in Fig. E5. The upper lateral ring support girder is an all-welded unit and ordinarily each weld joint would be numbered; however, because of the loading on this girder it is unnecessary. The girder generally acts to transmit loads from the steam generator in a smoother manner into the bumper pads and suppressors. The captured girder and lower lateral support girder should function satisfactorily in this capacity even if damage were present. For the lower lateral support girder, the compressive point load transmitted from the bumper block to the girder (beam) acts to wedge the girder into the surrounding cavity walls, capturing the members.

However, the column ends may be subject to lamellar tearing, and because of the similarity of the top and bottom ends, these are treated as only two joints as shown in Fig. E6.

The reactor coolant pump support structure has columns of the same general type as the steam generator (shown in Fig. E7). There is some ambiguity in the details at the base with gusset plates shown in Fig. E7 but omitted in Fig. E8. The column ends in both support structures as well as the tie bar ends can be characterized by joints of type 1 and 2. The parts called "pump stands" in Fig. E7 are not described in detail but appear to have welds of type 1 and 2 also.

The general conclusion on this plant is that there are no locations where lamellar tearing is particularly likely. This is primarily because of the post weld ultrasonic testing which was performed.

5.6.3 Miscellaneous Structure

The support structures in Surry were chosen to be an example of the miscellaneous class. The steam generator support structure is principally made of heavy castings so there are few places at which lamellar tearing is a concern. The upper restraint support shelves form one assembly which could not be dismissed. This bolted and welded assembly is shown in Fig. E10 and (in more detail) in Fig. E11. The three joints shown in Fig. E11 are in the upper restraint support assemblies upon which the weight of the upper ring restraint casting is supported. Since the weight of the steam generator itself is carried by the lower ring casting, the joints do not seem to be critical here but should be inspected in the interests of completeness.

The reactor coolant pumps are supported by a four-legged suspended structure with hydraulic shock suppressors carrying horizontal loads. The cross bracing rods between the main hangers are attached to the main hangers at clevises which are welded to the main hangers at a joint type labeled 4 in Fig. E13. These appear in several places, as shown.

The all-welded bracket at the bottom of the pump to which horizontal support legs are attached is shown in Fig. E14. All welding in this assembly can be labeled as joint type 5. This joint type has severe restraint but is mainly loaded in shear, producing somewhat offsetting effects. Inspection is in order here.

The horizontal braces shown in the horizontal support leg arrangement of Fig. E14 are also shown in the lower right hand corner of that figure. The attachment of the pipe to the square plate is labeled joint 6. This joint, however, raises a question as to whether the lamellar tearing would be visible near the middle of the plate edge. (The weld on the other side of the plate terminates at the edge where lamellar tearing, if present, would be visible, and should have been seen by post weld inspection.)

In summary, this facility has a few isolated locations where lamellar tearing might be a problem. Some care in inspection at these locations could clear this facility of any doubts.

5.6.4 Skirt Support

Arkansas Unit No. 1 is the skirt supported facility chosen for closer examination. The steam generator in this facility has a conical skirt welded near the bottom of the steam generator. This skirt in turn is welded to a flat plate bolted to the building foundation. The gusset plates in the skirt assembly are shown in Fig. E15 and joints 1 and 2 are identified. Note that the weld joint of parts 96 and 97 in detail L of Fig. E15 is not rated here since lamellar tearing would be visible at the free edge of part 97. This basic design is common to virtually all the skirt supported structures. It is felt that lamellar tearing damage here will degrade the structural capability very little, however. (Since this is a detail which is common to several plants, a careful study would be profitable here.)

The upper lateral support structure for the steam generator is a welded and bolted assembly of stubby beams and columns. The hanger rods for the coolant pump are also supported from this assembly. In spite of the large number of welds in this assembly, only two locations rated consideration One of these is embedded in the concrete secondary shield wall. The scope of this study did not include such embedments.

The other joint connects the tie-bar which carries loads from one beam assembly to the other. This joint carries such low through thickness stresses (2500 psi) that it will also be dismissed. Virtually all the joints either carry compression or shear in the through thickness direction. The shear loaded joints should rate some consideration. The structure has many parallel load paths which would pick up the loads if failure occurred at one or even several locations, however.

The reactor coolant pump has part of its vertical load carried by hanger rods supported as stated above. These present no problem. Cables and suppressors provide horizontal restraint. The cable system presents no problems for lamellar tearing, but brackets carrying the hydraulic suppressor loads to the concrete secondary shield wall require some attention. The general layout and details of this system are shown on Fig. E16 and Fig. E17. The wall plates are the most difficult joints here, particularly due to the awkward location for inspection.

In summary, the skirt to flange gusset reinforcements on the steam generator might be examined to determine the effect of lamellar tearing, not that this is a critical or worrisome location, but rather because it is common to several structures and should be simple to analyze. It also serves the purpose of deciding whether the materials used are susceptible. The remaining structure presents little concern except the wall brackets to which the hydraulic suppressors are attached. The tab test might be a desirable test for this assembly. (See Section 6.0)

5.6.5 Space Frame

Salem is the space frame structure chosen for further examination. The reactor coolant pump and steam generator use basically the same design concept. A very stiff all-welded assembly made up of I-beams and plate is used to contain the steam generator or pump. These assemblies are supported vertically and rotation prevented by two crossbraced plane frames pinned at each end as shown in Fig. E18. Lateral motion is prevented by stubby I-beam struts attached to the side walls.

An attempt was made to locate each of the weld joints and rate each. The upper ties of the steam generator are shown in plan view in Fig. E19 with some of the joints circled. After several sections had been examined it became apparent that the procedure developed for the other designs is marginally useful and very uneconomical. There are simply too many weld joints. One cannot isolate a few locations which can be spotlighted for further study. Essentially both structures are spotlighted in their entirety, a useless exercise.

It appears that a complete structural analysis might be performed with degraded but non-zero residual strength and increased flexibility at all points where lamellar tearing might be present. The other suggested procedure which might be used is an extensive weld tab test and inspection program. This would indicate the susceptibility of the construction materials.

FIGURE 5.1 DIAGRAM OF A PARTIALLY DEVELOPED LAMELLAR TEAR

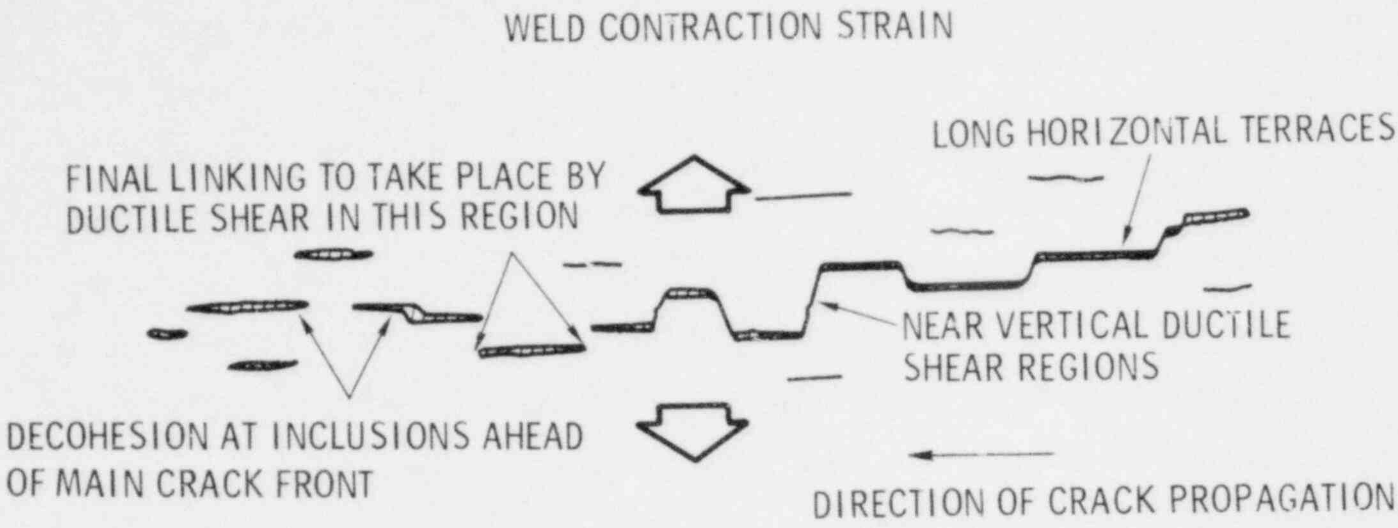
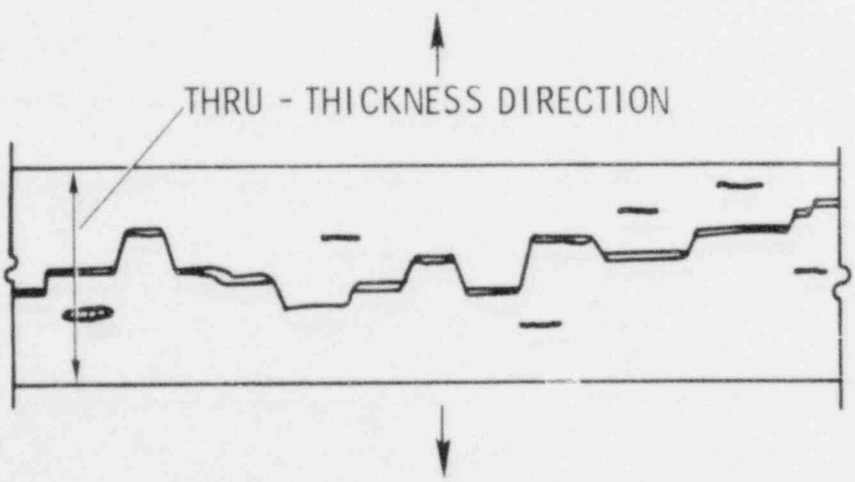


FIGURE 5.2 CROSS - SECTION OF PARENT MATERIAL SHOWING COMPLETE DEVELOPMENT OF INCOMPLETE TEAR SHOWN IN FIG. 5.1



6.0 Recommendations for Further Work

The next step in evaluating the brittle fracture susceptibility of operating PWR component supports would be to ascertain whether relatively higher susceptibility (Group I) plants can be shown to indeed be of low absolute susceptibility. Considering the hypothetical curve in Fig. 6.1 of stress versus temperature, for a given material with a given flaw or crack size, the stress at which the crack will propagate as a function of temperature can be determined. Very small cracks can be subjected to larger stresses without propagation so that the curves for two crack sizes vary as shown. If the stress and temperature in a member is below the curve for a given crack size, then this crack will not propagate. The plant groups were based upon a simplified curve of this type, namely the temperature at which the transition from brittle to ductile behavior takes place (under conditions of small crack size and near yield stress levels). The low susceptibility materials were those which are always at temperatures which place them in the ductile region (plateau of Fig. 6.1). Other methods of assuring that component support materials in specific plants have sufficient fracture toughness are outlined in the following sections.

6.1 Complete Utility Responses

Obtaining drawings and information from the plants which are in Group I, but for which there are incomplete responses to the initial NRC request, may allow some of these plants to be moved to Group II or III.

6.2 Operating Temperatures

The most direct method of assuring adequate ductility for a given material is to have the minimum operating temperature well above the NDT. Use of the cold shut down state in defining the minimum operating temperature is needlessly restrictive however. Operating procedures need to be considered, as a single temperature will not describe the state of a support at the time the reactor goes critical, due to heating from non-nuclear sources. Rather, a position-dependent temperature distribution will exist. Knowing this temperature distribution, and the distribution of material NDT values, one can then arrive at a more valid assessment of the structure. This is especially important in structures where questionable materials are found in only a few locations.

A careful temperature assessment would probably allow reclassification of several plants. An example, would be at the base flanges of steam generators in skirt supported units (where no other Group I material has been used in the structure). These temperatures could be obtained by measurements on the structures, by theoretical calculations, or by scale model experiments. The first method would be the most useful and would probably be the most economical. It may be possible to extrapolate the data from one plant to several installations.

6.3 Property Characterization

Another direct method of assuring low susceptibility is to show that the NDT for the actual material in a given structure is low. Most of the materials in Group I were placed there because the allowable variability in properties for these materials was so wide as to present the possibility that they have an NDT which is above the operating temperature range. But the actual curve of the type of Fig. 6.1 might be shifted much farther to the left than was postulated by the 95% confidence limit based upon a literature assessment. Two suggested ways to evaluate materials of specific plants are as follows.

The mill specifications where they are available might be examined for each structure. This is a relatively inexpensive approach but will not be sufficient for most cases. Chemical composition is only one of the variables which can significantly affect toughness.

Materials testing could be performed on samples removed from the actual structures. This would be expensive and should be preceded by very careful planning, but it would provide the most desirable assessment of toughness for specific supports.

6.4 Stress Analysis - In Service Inspection

If the operating temperature range does not lie completely in the ductile plateau region at the right side of Fig. 6.1, then the operating stress range must be shown to lie below the curve at the left side of Fig. 6.1.

This is the essence of fracture mechanics-guided design. It assumes a knowledge of three parameters: the stress acting, the size of crack present in a given geometry, and the fracture toughness of the material in which the crack is located. As discussed in Section 4.7, use of yield stress loads in conjunction with lower bound estimates of fracture toughness leads to some very small critical flaw sizes. In-service inspection may not be successful in detecting all cracks of this small size range, given the adverse conditions of access likely to be encountered in existing structures. Alternatively, very low design stresses (on the order of 5-8 ksi) can be allowed in the presence of large flaws after performance of a very careful stress analysis.

6.3 Material Testing for Lamellar Tearing

The preceding methods do not specifically apply to lamellar tearing. For structures in which lamellar tearing was found to be a concern, there is little which can be done except ultrasonic inspection at the locations of interest or material testing on the structural member.

Skinner (Ref 6.2) shows 29 different test configurations for lamellar tearing susceptibility, but most of these are expensive tests to perform. Porter (Ref. 6.3) gives a better description of several of these, together with comments about advantages and disadvantages, correlation work, usage and general acceptance of each. Two tests which are not described in these articles and which have the advantages of low cost and easy application to an existing structure are the following.

A relatively economical test called the "tab test" by Davey and Dolby (Ref. 6.4) can be performed as an extensive rather than intensive method. That is, many members could be sampled with this method for the same cost as a complicated and thorough test on a single sample. In this test a tab of unquestionable integrity is welded onto the plate to be tested as shown in Fig. 6.2. After cooling overnight the tab is broken by hammering in the direction shown.

The fracture face in the base plate is then examined to find the percentage of "woody" fracture area indicative of ductile fracture. Davey and Dolby state that "materials, in which the susceptibility to lamellar tearing is high and is not confined to the central regions, are detected easily by the test, and a 100% woody fracture appearance will be obtained." More lab tests should be made to validate the test but at this point it looks attractive because of its simplicity.

A second in-situ and relatively inexpensive qualitative method uses a small tab of sheet explosive (Ref. 6.5). In this test a 0.75 in. dia. piece of Datasheet C is placed in contact with the surface of the member. The very short compressive pulse from the sheet explosive is reflected from the free back surface of the plate as a tensile wave. This generates a tensile stress in the ST direction which sweeps the entire thickness of the plate. Any weak plane in the plate will be spalled and is easily detected under ultrasonic testing or (in the extreme case) noted as a visible bulge on one or both surfaces. The advantages of this test are low cost, short time to perform the tests, and few limitations on accessibility. The disadvantages are that extremely high strain rates are used here but not in the actual service loading. This may introduce errors for very ductile materials. Also, there is the (at least psychological) disadvantage of using explosives in a PWR plant.

In spite of the considerable space used in consideration of lamellar tearing in this report, the magnitude of the problem should be kept in perspective. Lamellar tearing has been identified in Section 5 as being possibly present in most of the structures at isolated locations and methods of verifying its presence or absence are suggested. However no analyses have been made to estimate the residual strength of a joint with lamellar tearing present. Welded fabrication methods and materials used here are common in buildings and other industrial support structures. It is reasonable to assume that the seriousness of lamellar tearing is generally the same in these structures. Since in-service failure caused by lamellar tearing is virtually non-existent (only one example could be found, Section 5.2) the residual strength must be rather high in joints which pass ordinary fabrication inspection.

A reasonable assessment is that a support structure may possibly be adequate even if lamellar tearing is present.

6.6 Fundamental Materials Research

A number of basic questions have been suggested by this program.

6.6.1 Static vs Dynamic K_{Ic}

In section 6.4 a fracture mechanics approach was outlined to predict critical flaw sizes. A necessary parameter for that approach is an accurate knowledge of the material fracture toughness. In low strength materials ($\sigma_y < 140$ ksi) fracture toughness has been shown to be a function of strain rate. To be conservative, dynamic values of fracture toughness were collected where possible for this report, and an empirical method used for obtaining "dynamic" values from static values. This method, derived by Barsom, could benefit from further investigation. Also, no weld metals have been tested, nor have any heat-treatment effects been studied.

6.6.2 Strain Rates Expected

It would be useful to obtain an estimate of worst case strain rates in actual support structures. The mass inertia in large structures usually dictates fairly low strain rates. But this need not be the case near the application points for severe loadings. In any case, even order of magnitude arguments would be an aid in assessing material requirements.

6.6.3 Orientation Dependence of K_{Ic}

It is well known that fracture toughness is orientation dependent in rolled shapes, at least at temperatures above the lower shelf. It is not obvious whether this is true on the lower shelf. If this dependence does not occur, it may mean that lamellar tearing does not further decrease the lower-bound estimates. This hypothesis has been assumed true in giving lower bound estimates of K_{Ic} in this report. Verification of this assumption is in order.

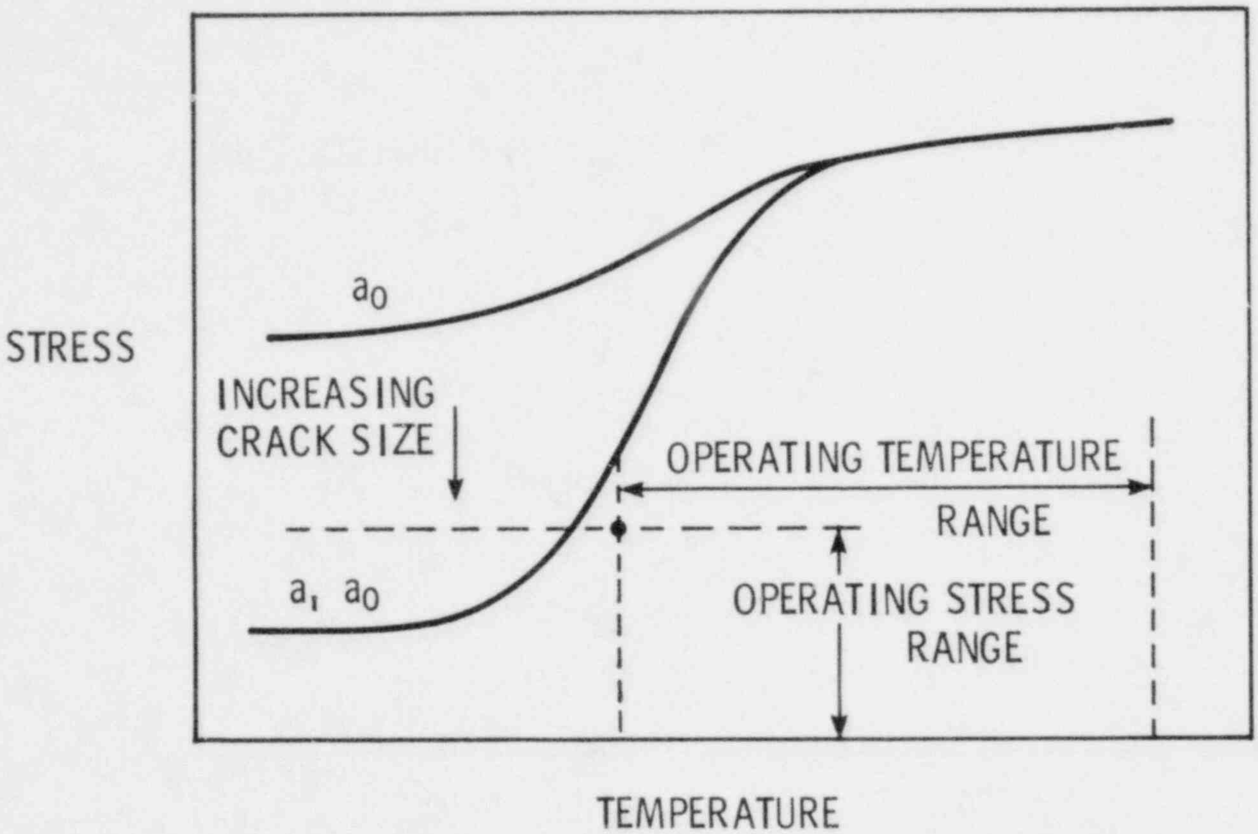


FIG. 6.1 CURVES OF STRESS AT WHICH CRACKS WILL PROPAGATE AS A FUNCTION OF TEMPERATURE FOR VARIOUS CRACK SIZES FOR A GIVEN HYPOTHETICAL MATERIAL.

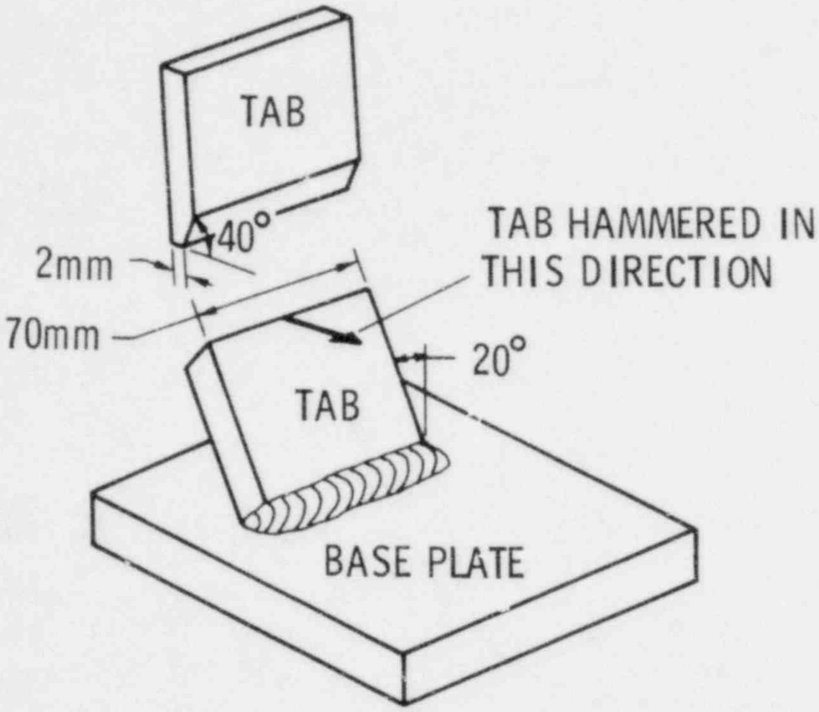


FIG. 6.2 TAB TEST FOR DETERMINING SUSCEPTIBILITY TO LAMELLAR TEARING

Appendix A

Component Support Summaries

Abbreviations

DL - Dead Load

TL - Thermal Load

OBE - Operating Basis Earthquake

DBE - Design Basis Earthquake

PR - Pipe Rupture

LP - Liquid Penetrant Test

MP - Magnetic Particle Test

UT - Ultrasonic Test

RT - Radiography Test

S_m - Maximum Allowable Stress

S_y - Yield Stress

S_u - Ultimate Tensile Stress

COMPONENT SUPPORT SUMMARY

PLANT Maine Yankee

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Yankee Atomic Power	Combustion Engineering	Stone & Webster	Sun Shipbuilding Newport News Shipbuilding

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-27 Gr 70-40 A-516 Gr 70 A-517 A-537 Gr B A-543-C-12 Gr B				CVN for some A-516, A-537 All A-543	Allowables and max. design listed by component	
Bolting Materials A-490 A-540 B23-Cl 4						
Weld Materials MIL 11018 MIL 120-S1						

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Manual metal arc Submerged arc		Stress Relief	Methods listed by component	MP all welds

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Sliding Pedestal	--	1. Normal 2. Upset + Emergency 3. Faulted	89°F

COMPONENT SUPPORT SUMMARY

PLANT Millstone #2

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Northeast Utilities	Combustion Engineering	Bechtel	PX Engineering

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS — NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS — THROUGH THICKNESS
A-106B A-302B A-515 Gr 65 A-533 Gr B-CL-2	Yes	A-302 Grade B Manufactured to Fine-Grain Practice	100% UT of A-302 and A-533		Load Given by Component	--
Bolts A-490 A-325						

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Sub. Arc Flux Core Arc Manual Metal ARC	AWS D2.0-69	Stress Relief	Use of AWS D2.0 joint designs	MP 10% UT of Full Penetration Welds

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Sliding Pedestal	--	DL + TL + PR + DBE	No minimum specified but expected to be above 115°F

COMPONENT SUPPORT SUMMARY

PLANT Palisades

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Consumers Power Company	Combustion Engineering	Bechtel	Pump-Ryerson

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-36 1020 A-514F A-540 A-302B A-307 A-212 A-193-B7 A-194-2H A-490 4140 1018 Weld materials E7018,E7028,F62-EL12,F70-EL12	Some mill certs. available	--	--	--	Steam Generator bending = 1.55 S_m = 40.05 ksi shear = 0.65 S_m = 16.02 ksi tension = S_m = 26.7 ksi	

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Manual metal arc Submerged arc	Unavailable for S.G. AWS D2-0-66 for Pump Supports	Stress Relief	Not Available	Magnetic Particle Following Fabrication Limited UT During In-Service Inspection

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Sliding Pedestal		Steam Generator DL + DBE + PR Coolant Pump Not Available	Estimated to be 100°F

COMPONENT SUPPORT SUMMARY

PLANT Calvert Cliffs 1,2

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Baltimore Gas & Electric	Combustion Engineering	Bechtel	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-36 A-302 A-501 A-533	Yes	--	--	--	AISC = DL+TL+OBE Allowable S_y { 1.1(1.25DL+PR+1.25 OBE) 1.1(1.25DL+1.25TL+1.25 OBE) 1.1(DL+PR+DBE) 1.2(DL+TL+DBE)	

Bolting Materials
A-490

Low-H Welding Materials

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Sub Arc Flux Core Manual Metal Arc	AWS-D-2.0-66	Heat Treatment (Charts Available)	AWS D2.0 joint designs	M.P.

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Sliding Pedestal	--	Combinations of DL, TL, PR, OBE, DBE	--

COMPONENT SUPPORT SUMMARY

PLANT Surry 1,2

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Virginia Electric Power Co	Westinghouse	Stone & Webster	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS THROUGH THICKNESS
A-105 Gr II A-106 Gr B A-285 Gr C A-352 Gr LC3 4340 Bolting Materials A-193 Gr B7 Vascomax 300 + 350	Yes			Vascomax & A-352		

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
	ASME Section IX		No heavy section intersecting members	All Welds LP or MP or RT UT-Vascomax and A-352

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Miscellaneous		DL + TL + DBE + PR	83°F

COMPONENT SUPPORT SUMMARY

PLANT Fort Calhoun 1

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Omaha Public Power	Combustion Engineering	Gibbs and Hill	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS THROUGH THICKNESS
A-36	No					
Bolting Materials A-307-GrA A-325 A-53-Type S-Gr B						

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
	"AWS & AISC Standard Codes for Welding"	Stress Relief		RT-Butt Welds MP-Fillet Welds

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Miscellaneous		To be supplied 12/31/77	80°F

COMPONENT SUPPORT SUMMARY

PLANT St. Lucie 1

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Florida Power and Light	Combustion Engineering	Ebasco	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-441 A-27 Gr 70-40 A-533-Gr-B-CL-1, CL-2 Bolting Materials A-325 A-307 A-193-B7 A-194-GP7 Weld Materials E70XX, F7X	Yes	--	--	--	Normal + Upset 1.5 S_m Emergency 1.8 S_m Faulted 1.5 $(S_y+1/3(S_u-S_y)$	50% of Normal Allowable Stresses

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Submerged Arc Manual Metal Arc	AWS-D2.0-1969	Stress Relief	Weld Joint Design	RT-Full Penetration Butt Welds UT MP or LP Full Penetration Tee Welds

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Miscellaneous	--	Combination of DL+TL+DBE+PR	60°F

COMPONENT SUPPORT SUMMARY

PLANT Yankee Rowe

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Yankee Atomic Electric Co	Westinghouse	Stone & Webster	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS THROUGH THICKNESS
Steam-Generator Support A-7 C-1020	No			Not Available		
Pump Support Cast Stainless Steel						

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
			Most Welds are Sized as 3/8" Fillet Welds	Inservice Inspections 1. Visual 2. UT on 2 pins and 6 bolts

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Steam Generator Support Space Frame			Majority of Support 500°F Lower Portion Calculated to be 200°F

COMPONENT SUPPORT SUMMARY

PLANT Salem 1,2

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Public Service Elect & Gas	Westinghouse	P.S.E.G.	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-441 Bolting Materials A-325 A-490 Vascomax 300 Camvac 200 Welding Materials E7016,17,18, E70-T1,T2 F71-EL12	Yes	Silicon Killed + Normalized A-441		CVN on A-441 (20 ft-lb @ 20°F)	Normal: AISC Allowables Upset: 1.33xAISC Allowables Emergency: 0.9 S_y Faulted 1.0 S_y	Max. Thru. Thickness Stress 19.23 ksi

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Manual Metal Arc Flux Cored Submerged Arc	AWS D2.0 with pre-heat dependent on thickness			M.P. at 4 weld depth UT where possible

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Space Frame	--	1. DL+TL - normal 2. DL+TL+OBE - upset 3. DL+TL+PR - emergency 4. DL+TL+DBE - faulted 5. DL+TL+PR+DBE - faulted	70°F

COMPONENT SUPPORT SUMMARY

PLANT H. B. Robinson 2

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Carolina Power & Light	Westinghouse	Ebasco	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-543 A-441 Pins + Bolts A-490 A-461 Gr 630 Welding Materials E70XX, F70-EM12	Mill Certs Available for A-543 A-441			None	Normal + Upset AISC Code Allowable Emergency .9 S_y Faulted S_y	60% of Allowable in Rolled Direction

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Manual Metal Arc Submerged Arc	Ebasco Specification WELC-5379-S15 AWS D2.0	Stress Relief		M.P. or L.P. All Welds U.T. Full Penetration Welds

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Space Frame	AISC (1963)	Normal + Upset DL + TL + DBE Emergency DL + Tl + OBE Faulted DL + TL + PR	65-70°F

COMPONENT SUPPORT SUMMARY

PLANT Beaver Valley 1

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Duquesne Light	Westinghouse	Stone & Webster	Westinghouse-Tampa Division

MATERIALS

					MAXIMUM ALLOWABLE DESIGN STRESS	
TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	NORMAL	THROUGH THICKNESS
A-36 Welding Material E7018 F72-EL12	Yes	--	All material thicker than 3 in. was U.T.	--	0.9 S_y (36 ksi)	DL - 4.4 ksi DL+DBE- 5.7ksi DL+DBE+PR - 16.3 ksi

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Manual Metal Arc Sub-Arc	ASME Sect. IX Qualified	Stress Relief	"Sound Engineering Practice"	Beaver Valley Spec. 349 Radiography or LP or MP Limited Joints: RT plus MP

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Space Frame	--	DL + DBE + PR No Normal Condition Analysis	83°F

COMPONENT SUPPORT SUMMARY

PLANT Haddam Neck

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Connecticut Yankee Atomic Power Company	Westinghouse	Stone & Webster	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-201 B A-216 WCB A-353 B	Yes	--	UT (A-216, A-201)	CVN on A-353-B	Tensile $0.8\ S_y$ Shear $0.4\ S_y$	Max. Stress Steam Gen. - 2.1 ksi Pump 3.8 ksi
Bolting Materials 4140 4340 A-193						

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
		Stress Relief of Ring Girders and Shell		MP Some Welds RT of Ring Girders and Shell LP on RCP Supports

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Skirt Supported		Steam Generator - DL + DBE + PR Pump - DL	90°-110°F

COMPONENT SUPPORT SUMMARY

PLANT Arkansas #1

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Arkansas Power & Light	Babcock & Wilcox	Bechtel	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-36 A-516-Gr 60 Bolts + Rods A-490	Yes		A-516-UT	A-516 Charpy	Tensile & Bending $0.9 S_y$ Shear $0.5 S_y$	Max 16.08 ksi

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Manual Shield Metal Arc Manual Flux Core Arc Semi-Automatic Sub Arc Auto Sub Arc	AWS D1.0-66	Stress Relief	Tension Members extended through cross members some places	Visual + Limited LP Initially UT After Repairing Visual Defect MP on all Following Completion

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Skirt Supported	--	Case 1: DL + DBE Case 2: DL + TL + DBE + PR	50°F

COMPONENT SUPPORT SUMMARY

PLANT Rancho Seco 1

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Sacramento Municipal Utility District	Babcock & Wilcox	Bechtel	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-508 Cl2 A-533 Gr B Cl1 A-515 Gr 70 Low-H Welding Materials	Yes		Some impact data available (not provided)		Normal+Upset $3\ S_m$ Emergency $1.5\ S_y$ Faulted $1.2\ S_y$ or $1.8\ S_y$	

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Submerged Arc Flux Core		Stress Relief		LP MP UT RT

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Skirt Su[illegible]		Normal + Upset Emergency Faulted	

COMPONENT SUPPORT SUMMARY

PLANT Three Mile Island Unit 1

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Metropolitan Edison Co	Babcock & Wilcox	Gilbert	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-302B A-515 Gr 70 A-533 Gr B Cl 1 Low H Welding Materials				None	Normal&Ups.. 0.5 (3 S_m) or 33.9 ksi Emergency 0.5 (1.5 S_y) or 27 ksi Faulted 0.5 (1.8 S_y) or 32.4 ksi	

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Submerged Arc Manual Metal Arc Flux Core	200°F preheat	Section III Stress Relief		Radiograph magnetic particle

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Skirt Supported		Normal and Upset Emergency Faulted	Not available

COMPONENT SUPPORT SUMMARY

PLANT Oconee 1,2,3

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Duke Power	Babcock & Wilcox	Duke Power	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-302B A-515 Gr 70 A-516 Gr 70 A-533 Gr B Cl 1 Low H Welding Materials	Yes				Normal+Upset 17.0 ksi Emergency 13.5 ksi (Primary Membrane Only) Faulted 24.[illegible] ksi	

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Sub Arc Manual Metal Arc Flux Core		Heat Treatment		MP All Joints Limited UT + [illegible]

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Skirt Supported		Normal + Upset Emergency Faulted	

COMPONENT SUPPORT SUMMARY

PLANT Davis-Besse 1

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Toledo Edison	Babcock & Wilcox	Bechtel	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-516 Gr 70 A-36 A-387 Gr-22 CL-1 A-576 Gr-1018 A-320 Gr L7 A-182 Gr F-22 A-53 Gr B Bolting Materials A-540 A-193 A-490 Low-H Welding Materials	Yes	A-516 and A-36 Manufactured to fine grain practice A-36 Silicon-Killed and fine grain practice if 5/8"	--	CVN Requirement for matl. 5/8 in. (15 ft-lb @ 0°F or NDT 0°F)	Normal f_s-Allowable AISC Upset 1.25 f_s Emergency 1.5 f_s Faulted 1.5 f_s	--

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Sub Arc Shielded Metal Arc Flux Cored	AWS D2.0-69	Heat Treatment on all welds 1-1/2 in	AWS D2.0 joint designs	All welds MP or LP Butt Welds RT Fillet Welds 1/2 in 10% UT Full Penetration T Welds 10% UT

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Skirt Supported	--	Normal Upset Emergency Faulted	50°F

COMPONENT SUPPORT SUMMARY

PLANT Crystal River 3

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Florida Power	Babcock & Wilcox	Gilbert	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-533 Gr B CL 1 A-302 B A-515 Gr 70 A-516 Gr 70 Low-H Welding Material	Yes		Some UT		Normal+Upset 0.5(3 S_m) or 33.9 Emergency 0.5 (S_y) or 18 0.5(1.5 S_y) or 27 Faulted 0.5(1.2 S_y or 21.6 0.5(1.8 S_y) or 32.4	

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELIAR TEARING	NDE AND INSPECTIONS PERFORMED
Sub Arc Manual Metal Arc Flux Core		Stress Relief		MP or RT

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Skirt Supported	B31.7 (1968)	Normal + Upset Emergency Faulted	

COMPONENT SUPPORT SUMMARY

PLANT Prairie Island 1,2

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Northern States Power	Westinghouse	Fluor-Pioneer, Inc.	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-588 A-514 Bolting Materials A-193 B7 A-194 Gr 7 Welding Materials E7018, F70-EL12	Yes	A-588 was normalized (> 3" in Unit 1, All in Unit 2)	100% UT of Plates, (except 1/4 in or thinner) Bolts, Nuts, and Pins (> 2 in dia)	CVN requirement for A-588, A-514F, Weld Materials, HAZ Bolt Materials 1.5 in (15 ft-lb @ 40°F)	Normal AISC Manual Allowables Faulted 1.5x(AISC Allowables)	Max. Faulted 32.3 ksi

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Manual Metal Arc Auto Sub Arc	Conform to Sections VIII and IX	Heat Treatment	Several Thinner Members Used to Replace Thick Sections Weld Restraint Minimized	LP of Weld Prep MP of Root Pass and Subsequent Passes UT of Full Penetration Welds

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Pin-Column	--	Normal: DL + TL Faulted: DL + TL + DBE + PR	70°F

COMPONENT SUPPORT SUMMARY

PLANT Trojan

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Portland General & Electric	Westinghouse	Bechtel	Fought & Co.

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-36 Bolting materials A-193 B-7 A-354 Gr BC A-540 B24-Cl-1 A-540 B-23-Cl-1 Welding Materials E70XX	Yes				DL + TL AISC Manual Allowables All Faulted Conditions 1.5x(AISC Allowables) or 0.9 S_y	Only 2 Locations Greater than 50% of Allowable (these 2 are at 75% of allowable normal value)

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Manual Metal Arc	AWS D1.0-1969		AWS Joint Designs	UT on Pin Plate Attachment Visual

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Pin-Column		Various Combinations of DL + TL + DBE + PR* *Several Pipe Rupture Scenarios	Ambient Air: 50-120°F Expected Min of Support: 90°F

COMPONENT SUPPORT SUMMARY

PLANT Donald C. Cook 1,2

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Indiana & Michigan Power	Westinghouse	American Elect P. Co.	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-36 A-588 Bolting Materials A-193 B7 A-194 Gr7 Welding Materials E60XX, E70XX 8016, 18-C1 8018-G 8016, 18-C2, 2-1/2 or 3-1/2 Ni Content sub arc consumables	Yes	A-36 to fine grain practice Normalized A-588 in Critical members	UT under weld areas	Thru-Thickness Reduced Area Tests CVN for A-36, A-588 (15 ft-lbs @ 30°F) Also HAZ and Weld Materials	Normal-Upset AISC Manual Allowables Emergency $0.9\ S_y$ Faulted Non-Linear Elastic-Plastic Analysis	$0.65\ S_y$

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Manual Metal Arc Sub-arc	AISC Code, Section IX Qualified Procedures	Stress Releif	AISC Code Joints	UT or RT where possible MP or LP

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Pin-Column	--	Normal: DL + TL Upset: DL + TL + OBE Emergency: DL + TL + DBE Faulted: DL + TL + DBE + PR	60°F

COMPONENT SUPPORT SUMMARY

PLANT Zion 1 & 2

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Commonwealth Edison	Westinghouse	Sargent & Lundy	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-36 A-588 Bolting Materials A-193 B7 A-194 Gr 7 Low-H Welding Material		A-36 to fine-grain practice A-588 normalized if 3 in. thick	UT under weld areas	CVN Requirements (15 ft-lbs @ 0°F) for A-36, A-588 Weld Metal & HAZ Thru-Thickness Tensile Tests	Normal AISC Manual Allowables Faulted S_y (Except controlled area)	0.6 S_y

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
	ASME Section VIII	Stress Relief	AISC Joint Designs	LP RT UT 100% under welds

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Pin Column	1963 AISC	1. DL + TL 2. DL + TL + DBE 3. DL + TL + OBE 4. DL + TL + PR 5. DL + TL + PR + OBE	71°F

COMPONENT SUPPORT SUMMARY

PLANT Kewaunee

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Wisconsin Public Service	Westinghouse	Fluor-Pioneer, Inc.	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-588 A-514F A-490 Weld Materials E7018 F70-EL12	Yes	A-588 over 3" Normalized	UT	CVN on Structural, HAZ Weld, Bolting Materials (15 ft-lb @ 40°F)	Normal AISC Allowable Faulted 1.5x(AISC Allowable)	

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Manual Metal Arc Auto Sub Arc	To ASME Section VIII, IX		1. Use of several thin members instead of single thick members 2. Double welded joints to reduce weld volume 3. Minimize weld restraint	LP MP UT on Full Penetration Welds

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Pin-Column	--	Normal: DL + TL Faulted: DL + TL + DBE + PR	70°F

COMPONENT SUPPORT SUMMARY

PLANT Point Beach 1,2

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Wisconsion Electric	Westinghouse	Bechtel	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-36 A-53 A-441 A-514 A-517 F Bolting Materials A-322 A-490 1015-1020 Welding Materials 7015, 16, 18; E70T-1, T-5, SAW-2(?)	Yes				Not Available	

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Manual Metal Arc Submerged Arc Gas Metal Arc	AWS D2.0	Stress Relief	Buttering of A-514 A-517 Welds	MP of All Joints UT of Joints with "T-1"

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Pin Column	--	Not Available	85°F

COMPONENT SUPPORT SUMMARY

PLANT R. E. Ginna

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Rochester Gas & Electric	Westinghouse	Gilbert	

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS: NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS: THROUGH THICKNESS
A-36 A-514 Gr B, H, F USS "T-1" Bolting Materials A-194 Gr 2H A-490 A-193 Gr B7 USS "T-1" Welding Materi E-7018, E-11018 M	Partial				DL + PR "T-1"-0.9 F_y Tension + Bending or 0.75 Su A-36 - 1.0 F_y Tension + Bending	

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Manual metal arc	Qualifed to Section IX or AWS D1.0 for 110XX	None	No heavy inter-secting T or corner joints	MP or LP Full Penetration Welds 100% RT Where Possible

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Pin Column		1. DL + OBE 2. DL + DBE 3. DL + PR	Min. Design Temp. 120°F No Measurements Made

COMPONENT SUPPORT SUMMARY

PLANT J. M. Farley 1 & 2

UTILITY	NSSS	AE	SUPPORT SUPPLIER
Alabama Power	Westinghouse	Southern Services/ Bechtel	Pittsburgh-Des Moines

MATERIALS

TYPE	MILL CERTS. AVAILABLE	HEAT TREATMENT	NDE ON MATERIAL	FRACTURE TOUGHNESS TEST	MAXIMUM ALLOWABLE DESIGN STRESS NORMAL	MAXIMUM ALLOWABLE DESIGN STRESS THROUGH THICKNESS
A-537 A-572 Gr 50 A-441 A-36 A-514 A-106 Gr C A618 Gr II A-322 Bolting A-490 Materials Welding Material E7018, E8018-C3, E11018-M F71-EL12,E70-T1	Yes		UT on material which would have thru-thickness stresses	CVN for plates, shapes or pipes 0.5 inches min. average of three specimens H.R. or normalized 13 ft-lb @ 0°F Quenched+tempered 20 ft-lb @ -30°F Bolting materials 30 ft-lb @ 0°F Electroslag Metal & HAZ	actual and allowable loads listed by member	

FABRICATION

WELDING PROCESS	WELDING PROCEDURE	POST-WELDING TREATMENT	METHODS USED TO PREVENT LAMELLAR TEARING	NDE AND INSPECTIONS PERFORMED
Electroslag Shielded Metal Arc Submerged Arc Fluxed Cored Arc	Qualified to Section IX	Stress relief of sections greater than 1-1/2 inches Electroslag weldments were normalized at 1650°F for 30 minutes	Use of electroslag welding, or small fillet welds	RT - Butt welds UT - Full penetration tee or corner welds MP or LP on remainder MP on all fillet

DESIGN

TYPE OF SUPPORT	CODE USED	LOADING CONDITIONS	MINIMUM TEMPERATURE OF SUPPORT
Pin Column		Normal - DL + TL Upset - DL + TL + 1/2 DBE Faulted - DL + TL + DBE + PR	120°F

APPENDIX B - MATERIAL DATA

B.1 Data Obtained

The sources of material data for the various groups are listed in Tables B.1 through B.7. Included in these tables are data sources which were not used in the body of the report. The actual data (NDT and K-type) have been plotted in Figs. B.1 through B.25. Tabulation of $\overline{NDT}$ data and standard deviations (where possible) are indicated in Table 4.4.

NDT data for several grades of steel were not located. Assignment into susceptibility groups for these materials were based on the minimum requirements of the appropriate standards under which the materials were procured (see Appendix C), as compared to materials for which data were obtained.

B.2 Cast Steels

Four grades of cast steels were listed in the utility submittals (not counting a stainless steel casting for Yankee, considered not to have a problem with respect to fracture toughness or lamellar tearing). Two of the grades, A-27 Gr 70-40 and A-216 Gr WCB are carbon manganese-silicon types; one, A-148 (Gr 80-40 and Gr 80-50) is not chemically specified (which indicates it may be either C-Mn or low-alloy depending upon the heat treatment and/or section size) and the last, A-352 Gr LC3, is a high (3-4%) nickel content heat-treated alloy requiring CVN testing. (Note: all % are by weight)

The A-352 Gr LC3 grade in either the double normalized and tempered, or quenched and tempered condition is expected to show excellent fracture toughness with NDT's in the range of -100°F for

1" section size (Fig. B.1). Some utility data (Ref. B-1) indicated thick section NDT's in the -100 to -60°F range with a maximum value (one example) of -20°F.

A-27 Gr 70-40 and A-216 Gr WCB are both C-Mn-Si type alloys varying only slightly in chemical composition allowables, and primarily in minimum yield strength (40 vs 36 ksi, respectively). Of the two, the A-27 Gr 70-40 allows less carbon (.25% vs .30%) but more manganese (1.2% vs 1.0%). A-216 Gr WCC is virtually identical to A-27 Gr 70-40 in this respect. A histogram of NDT values for A-27 Gr 70-40 heats mainly in the normalized and tempered condition (five were normalized and four were quenched and tempered) plus five heats of A-216 Gr WCB is shown in Fig. B.2. This is taken from a compilation made by the Steel Founder's Society of America (Ref. B-2). The statistics of these data imply that 95% of all heats have NDT's below 20°F. However, these data are taken from 1" thick test castings, and a section size effect may be expected. A second source of data (Ref. B-3) for these materials indicated that NDT was 35°F with a standard deviation (σ) of 17°F for 12 specimens of varying thickness (from 2-1/2" to 5") poured from two heats in the normalized and tempered condition. This still indicates that 95% have their NDT below 70°F, but not with as much margin as the 1 in. thickness case. Finally, these two specifications allow the possibility of producing heats in the annealed condition, if the mechanical properties can be met. This would be expected to further degrade their fracture toughness properties since a coarser microstructure would result. This implies the only way to meet strength requirements would be by increasing carbon content.

Finally, A-148 Gr 80-40 and Gr 80-50 (40 and 50 ksi yield strength, respectively) are more difficult to evaluate, since chemical specifications and data are lacking. The added strength requirements over A27 Gr 70-40 could be met in a number of ways; via heat treatment, via additional carbon content, or via alloy content. Since additional carbon is usually the least expensive route, the implication is that these sub-grades of A-148 would have less desirable NDT values than the previously discussed A-27 and A-216. However, A-148 was specified by only one plant and was part of a wire rope system, which is probably not as critical a location as the other cast grades, which were typically in the sliding pedestal category of plants. In Fig. B.1 some NDT data (Ref. B-4) is available for normalized and tempered A-148 Gr 80-50 which indicate excellent NDT's around -10F; however, these heats contained approximately 2% Ni. Thus these data would be indicative of the best practices in meeting the mechanical property requirements.

K_{Ic} data were located for two heats of A-216 Gr WCC (Refs B-5, B-6). These are shown in Figs. B.3. Applying a temperature shift of about 150°F, equivalent K_{Id} values at 75°F are roughly 40 ksi $\sqrt{in}$. These specimens were taken from immense (20"x20"x48") castings, and probably represent the worst possible section size effect.

B.3 Weld Consumables

The weld metals are also in the cast steel category. It is difficult to evaluate weld metal properties separately from the base materials being joined, since dilution effects can occur which significantly change the chemical composition of the fused metal. Furthermore, specifying that an AWS E 70XX electrode was used does not specifically define the composition because of variability between different welding consumable suppliers. For these reasons and others, the AWS requirements of CVN testing for all-weld-metal specimens are only a first step in assuring fracture toughness; however they are a very useful first step, especially in weldments where the weld is not diluted excessively, which is true for thick section multipass welds common to these support structures. The matter of heat-affected zone properties will be treated in later sections on individual base metal groups.

A number of utilities supplied incomplete information with respect to the welding procedures. Among these were most of the skirt-supported structures, where a process was specified but no specific materials were identified, and the sliding pedestal structures, where a process and "low-hydrogen" consumables were specified.

The opposite situation existed for some of the pin-column structures where complete (CVN) testing of the materials (plate, weld metal and heat-affected zones) was required.

From those licensee submittals which were detailed enough to indicate the AWS specifications under which welding consumables were procured, the list of processes and consumables noted in Table 3-1 was compiled. The AWS CVN impact requirements for the following grades are:*

E7015, 7016, 7018	20 ft lbs @ -20°F as welded
E8016 C-1, 8018 C-1	20 ft lbs @ -75°F stress-relieved
E8016 C-2, 8018 C-2	20 ft lbs @ -100°F stress-relieved
E8018 C-3	20 ft lbs @ -40°F as welded

*One specimen may have a value as low as 15 ft-lbs, but average of 20 ft lbs is required. The highest and lowest values of 5 specimens are disregarded.

E11018-M	20 ft lbs @ -60°F as welded
F71 EL 12	20 ft lbs @ 0°F as welded
F72 EM 12K	20 ft lbs @ -20°F as welded
E70 T-1	20 ft lbs @ 0°F as welded
E70 T-5	20 ft lbs @ -20°F as welded

The following specifications are not required to meet any impact requirements.

E8018-G	(E8018-G was used only at D. C. Cook where it had to meet a CVN of 15 ft-lbs @ 30°F)
E70 T-2	
F70 EL-12	
F70 EM-12	

The 20 ft lb CVN requirement at a given temperature is approximately equivalent to specifying the deposit NDT temperature.

These CVN tests are run using either ASTM A-36, A-283D (not for the alloyed electrodes E 80XX-X, E 110XX-X) or A-285C plate materials; however, in testing the alloyed electrodes the surfaces of the weld preparation are "buttered" (an overlay technique), and thus the dilution of the weld deposit is reduced.

The AWS required tests are made from multipass weldments in the flat position which are supposedly representative of common commercial practice. The support structures of interest are generally in the stress-relieved condition, whereas the AWS test procedure mostly refers to the as-welded condition. This may make some difference, as stress relief can be deleterious (Ref. B-7) especially for some electrodes used to weld A-514/A-517 steels (Ref. B-8). Several opposing factors are present; stress relief lowers the magnitude of residual stress present, which is beneficial, and it also removes the effect of any strain-aging or quench aging embrittlement which may be present. However, in deposits containing elements which may cause age hardening, (e.g., Ti, V, Nb, B, Al, Mo, Cr) an increase in yield strength and decrease in toughness may occur with stress relief. Decomposition of retained austenite to coarse carbide aggregates may also occur. Thus the benefits of stress relief are not clear-cut, because of the complicated influences on microstructural variations of alloy content and heat input (Ref. B-9).

C/Mn weld deposit toughness will in general benefit from stress-relief except at very low heat inputs, while toughness for deposits containing age hardening elements will depend upon the microstructure developed as a result of the composition and thermal history of the weld. Commercial practice usually results in using lower alloy content weld metal and higher heat inputs, both conditions tending to yield lower amounts of acicular ferrite in the weld deposit, which according to Dolby (Ref. B-10) would lead to an increase in toughness on post weld heat treatment. However, for the as-welded state, higher levels of acicular ferrite (up to 90%) are best.

Unfortunately, without much more specific information as to welding procedural details than has been made available in the utility responses, it is impossible to discuss individual plants.

Even for materials meeting AWS CVN specifications, deviations from the procedure under which they were originally tested can result in different and perhaps inferior notch toughness. For those materials not meeting any CVN specifications the situation is more uncertain with respect to predicting their toughness properties.

Comments about specific processes follow.

B.3.1 Shielded metal-arc

For basic-coated low hydrogen electrodes, weld metal toughness is generally adequate-to-excellent, depending upon the alloy content of the electrode. A difficulty which may be encountered is the possibility of reduced root pass toughness in thick section multipass weldments (Ref. B-11). To some extent this problem may be reduced by back gouging and stress-relief.

The multiposition capability of the "stick" electrodes specified means that they can and will be used in vertical and overhead welds. It has been determined that toughness will decrease depending upon weld position in the following order: flat, horizontal, overhead, vertical (Ref. B-12). The change in the 20 ft-lb transition temperature between flat and vertical positions may be 40°F. This is due in part to the relative amount of heat input required for the various positions, and reflects the general tendency of toughness to degrade with increasing heat input (Ref. B-13). Exceptions to this trend might be encountered where increases in heat input serve to increase toughness due to microstructural transitions. For example, structures of C-Mn weld metals at low heat inputs ($<$ 40 kJ/in) may show a decrease in toughness upon post welding heat treatment due to decomposition of retained austenite. For vertical welds, the heat input might increase in the regime where stress relief improves toughness.

B.3.2 Submerged Arc

This process is popular because of its ability to provide high metal-deposition rates. It has traditionally been suspected of providing low-toughness weld metal, though such claims can no longer be considered accurate. Part of the reason for its reputation as a poor toughness process has to be connected with its high heat input. When used at lower heat inputs, there does not appear to be any reason why excellent toughness should not result (Ref. B-14). With the recent development of more basic fluxes, the weld metal can be as tough as that deposited with manual electrodes.

However, the choice of an F-70-XXXX submerged arc process and the absence of supplementary impact testing lead to the belief that metal deposition rates are the primary concern of the designer. This implies that high heat input conditions and consequently lowered toughness will result. Toughness values for F70-XXXX welds do not commonly exist. On the other hand, submerged arc weld toughness values which do exist are not commonly classified according to the AWS flux classification system. Thus there is no good basis for assigning an NDT value to these welds. About all one can do is to look for data pertaining to high weld heat input and assume that the lower bound toughness applies to F-70-XXXX class welds. One collection of data (Ref. B-15) which might be applicable is shown in Fig. B.4, which indicates that two or three pass submerged arc welds may exhibit NDT's of up to about 60°F. The original reference was not obtainable, and statistical analysis is not possible. Other sources, (Refs. B-16, B-17 and see Fig. B.5 and B.6) indicate that 20 ft-lbs at 32°F may be readily obtainable in two pass submerged arc welds. All of these references (B-15, B-16, B-17) refer to non-stress-relieved welds; the effect of stress relief is probably beneficial (as the F-70 consumables probably have the simplest composition) but this point cannot be stated with certainty.

B.3.3 Flux-cored Arc

Of the three specifications called out for this process, two have to meet impact standards. The same reasoning applies to them as to the previously discussed manual and sub-arc classifications with the same requirement.

E 70-T2 specification weld metal (which lacks a CVN requirement) appears to be used primarily in single-pass welds; it uses a high titania slag, and is not considered the best choice for high toughness; yet, one data source (Ref. B-18) indicates that welds made to this specification can produce CVN results better than some E 70-T1 welds which must meet minimum CVN requirements.

Since this is usually a single pass consumable, it may not be extensively used in actual structural welding (it was only specified by Salem) but may instead be used for non-critical applications such as attaching temporary backing bars, nameplates, spoiling bolt threads, etc. There is not specific evidence available which proves or disproves this speculation; however, for the Salem plant all the other welding processes noted had to meet minimum CVN requirements, which indicates that toughness was a design consideration.

B.3.4 Electro-slag welding

Only one plant (Farley) noted the use of electroslag welding, and in that case normalization and impact testing at 10°F were required.

The question arises as to how to analyze plants which did not adequately specify the welding process or consumables used. In most cases (notably a number of skirt-supported plants) other factors resulted in these plants being placed in high risk groups. Lack of specific weld consumable information influences only one plant, Connecticut Yankee, which was lowered from Group III to Group II because of the lack of certainty about its welds.

B.4 Base Materials

The base materials have been divided into the following categories of materials: Plain Carbon, Carbon-Manganese, High-Strength Low Alloy, Low Alloy, and Quenched and Tempered steels.

B.4.1 Plain Carbon ("Mild") Steels

Plain carbon steels are best characterized as variable. Some grades within this category have essentially no chemical controls, while others have specific composition controls. However, even for those grades which are composition-controlled, the limits imposed are not stringent enough to effectively control fracture toughness. The main reason for the controls (where they exist) appears to be an attempt at insuring weldability. To some extent this can aid fracture toughness (by limiting C), however it can also be harmful (by limiting Mn).

NDT data obtained for steels in this category are plotted in Fig. B.7. The spread in NDT values is enormous, from quite good to poor. The relatively few NDT values obtained reflect the fact that many of these steels are pressure vessel grades, and are commonly used at higher temperatures; thus there is limited emphasis upon their low temperature properties. Some NDT data, especially for A-106, are correlated from pre-cracked Charpy (PCC) or DWTT specimens. It is interesting to note that A-212 and A-515 specimens in the normalized state still have relatively high NDT temperatures; this contrasts markedly with data in the C/Mn and HSLA categories. Because data for A-201 is consistently at the low temperature end of the plain carbon steel distribution, it is difficult to determine if A-201 belongs in this class or not. The five normalized points reinforce the five in the as-rolled condition. Also, this is consistent with the normalized A-515 and A-212 where the decrease in NDT due to normalization is small. Therefore, A-201 will be considered a Group II material rather than Group I. The statistical analyses of mean and standard deviations are noted in Table 4.4. These values appear to coincide with a qualitative figure published by Pellini, et al., (Fig. B.8). The relatively few K-type measurements are plotted in Fig. B.9. A value of 32 ksi $\sqrt{in}$ appears to be the lower bound.

B.4.2 Carbon-Manganese Steels

Fine grain size is effective in improving both strength and toughness of steels. The C/Mn steels use this effect by including manganese to promote fine grain size, and at the same time carbon is restricted to lower levels than would be necessary in a plain-carbon steel. Also, fine-grain melt practice (addition of Al, or other suitable nitride-formers to restrict the growth of austenite grains at high temperatures during processing) further reduces grain size in some grades.

The inclusion of A-105 in this category is somewhat questionable because the Mn minimum specified is not very restrictive (0.6 Mn; normal mild steel steelmaking practice approaches this level), and the maximum allowable carbon content (0.35) is quite high. For this reason, A-105 in the as-forged condition, i.e., not heat-treated, was included in the mild steel risk group.

In obtaining data for this category it was considered appropriate to include data from A-131, the ASTM equivalent of the ABS ship plate grades. Grades A, B and C correspond to this category in the as-rolled condition.

While the inclusion of manganese and fine grain practice additions help to control the as-hot-rolled grain size, the use of a normalization treatment enables maximum benefit to be gained from these techniques. This heat-treatment produces a fine austenitic grain size, which is not allowed to coarsen during the normalization process. Thus the prior austenitic grain size is characteristic of relatively low temperatures, rather than the higher tempertures characteristic of hot rolling. The Mn also lowers the transformation temperature, which further serves to refine the microstructure. The benefits are obvious when the NDT values for normalized materials (Fig. B.10) are compared with those in the non-normalized condition (Fig. B.11). APS grades CS and CN are included with the normalized data. Statistical analysis of the data is noted in Table 4.4. The K-type data is summarized in Fig. B.12. A reasonable lower bound appears to be 36 ksi $\sqrt{in}$.

B.4.3 High Strength Low Alloy (HSLA) Steels

The words "high strength" as applied to high-tonnage structural steels do not imply the same meaning as when applied to steels in general. (For steels in general, "high strength" applies to those with yield stress greater than 180 ksi, "low strength" applies to those with yield stress below 90 ksi, and "medium strength" to those in between.)

In the context of HSLA steels, "high strength" means a yield level above about 40 ksi. This category of steels uses the same technique as the previous category -- fine grain size -- to achieve high strength and good toughness at the same time. The difference between the two is that the HSLA steels use alloying additions (principally Nb and V) which actively promote stable precipitates which provide an added increment of strengthening. However, the toughness is critically dependent upon the rolling schedule. A temperature which is too high during final rolling will cause the grain-refining precipitates to dissolve, resulting in a coarse grain size, and an exceptionally high impact transition temperature due to the high strength level caused by precipitation hardening after the grain-coarsening takes place.

Normalizing treatments act in the same way for these steels as in the C/Mn fine grain practice steels, as long as the precipitates aren't allowed to dissolve. A normalizing treatment will not result in the best possible combination of strength and toughness in these steels, but it will ameliorate the effect of incorrect rolling practice. Since the mill rolling force required increases with plate thickness, higher rolling temperatures are used to keep the rolling force at a suitable level. It is thus clear that higher thickness HSLA plate would be most susceptible to incorrect rolling practice, resulting in a high NDT.

A noticeable difference in NDT values for normalized versus as-rolled HSLA steels is indicated in Table 4.4. The two main sources of data are noted in Table B-8.

As can be seen, the normalized plates appear to be much tougher than the as-rolled plates, though their distribution is unknown. A postulated distribution similar to that of the normalized C/Mn steels, σ = 18°F, would imply that 95% of all normalized HSLA steels have an NDT temperture below about 0°F (at least for thicknesses below 1-1/2").

Table B.8
NDT Data for HSLA Steels

rce	Grade	Thickness	NDT (°F)	# Heats	Heat Treat
Von Rosenberg	A-572	1"-1.5	20-50°	12	prob. as rolled
Kuang [B-20]	A-572	.75-2.5	10-40°	11	prob. as rolled
	A-572	.625-1.5	ave. 24° σ = 11°	15	as-rolled
Hodge	A-572	.5-1.5	ave.-54° σ = ?	8	normalized
MPC	A-441	.75-1.25	ave.-45° σ = ?	5	normalized
[B-19]	A-441	2"	ave. 10° σ = 8°	4	as-rolled
	A-441	.75-1.25	ave. 2° σ = 4°	6	as rolled

For the as-rolled plates the situation is quite different, however. Apparently a significant fraction of heats have NDT above about 25°F. The two data sources seem reasonably compatible if one assumes a standard deviation of about 12°F, similar to the 11°F suggested by source 2. This would seem in line with a global average of 25°F (assuming the midpoints of the ranges specified by source 1 act as average values for their respective ranges).

Data for which individual determinations of NDT are available are plotted in Γ 13. Except for three data points known to be as-rolled (30°F, 80°F, 100°F), the remainder are of unknown heat treatment.

These yield an average NDT of 6°F with a standard deviation of 50°F. It is likely that more than one heat treatment is included.

Of all the data known, totalling 73 heats, only 2 have NDT above 75°F (this assumes that none of the heats tabulated by source 2 in Table B.8 has an NDT this high; upon examination of the reported averages and standard deviations, this seems reasonable). Subtracting 20 heats known or presumed to be in the normalized condition, this still leaves only 2 out of 53 with NDT above 75°F.

In general, the incorrectly processed material appears to be rare. K-type data is summarized in Fig. B.14, a lower bound value is 36 ksi $\sqrt{in}$.

B.4.4 Low Alloy (Non-Quenched and Tempered) Steels

These grades generally contain enough alloy content to prevent their transformation to ferrite-pearlite microstructures. Instead bainitic or martensitic microstructures form, which generally have higher strengths.

A-302B has been used as a pressure vessel steel in several nuclear reactors, and has been investigated quite thoroughly as a result. Most of these studies are concerned with much thicker section material than would be used in support structures and the results would be overly pessimistic when applied here. Limited NDT determinations (Refs. B-24-B-28) were found for this material. Values of NDT in the as-rolled condition were: 20, 50, 55°F, and in the normalized condition: -30, -30, -20, -10, - 10, 0, 5, 10, 20, 40°F. An overall average and σ are noted in Table 4.4. Additionally, one older source (Ref. B-27) noted an NDT of 110°F without revealing heat treat condition. This reference stated that an extensive survey was made which resulted in specifications being accepted by the steel mills of 30 ft-lb CVN at 10°F for Navy pressure vessels. Apparently this resulted in improved steel-making practice for A-302 subsequent to 1955. K-type data (Refs. B-28-B-31) is tabulated in Table B.9. From the tabulation, at 60°F a lower limit of 30 ksi $\sqrt{in}$ is suggested by 2 of 13 data points (one of these is in the annealed condition; although normalization is proper for 2" plate thicknesses). A span of 37 to 45 ksi $\sqrt{in}$ encompasses 6 out of the 13 points, with the remaining 5 at higher values.

A-322 was specified by two plants. This specification includes hot-rolled alloy steel bar stock, and contains a multitude of AISI alloy grades. However, both plants that utilized this category material specified AISI 4340 at a tensile yield of 145 ksi minimum. At this medium strength level, the Structural Alloys Handbook (Ref. B-32) indicates K_{Ic} values in excess of 100 ksi$\sqrt{in}$. (K_{Ic} should not differ substantially from K_{Id} at this yield stress level.)

A-353 is a cryogenic grade of steel; its high 9% Ni alloy content assures that it will transform to non-pearlitic microstructures except under non-standard fully annealed (furnace cooling) conditions. The specified double-normalizing treatment ensures fine grain structure, and the tempering treatment allows the formation of a small percentage of austenite (which remains stable, and improves low-temperature properties). Cooling from the tempering temperature must be rapid in order to avoid embrittlement noted in martensitic grades. Pense and Stout (Ref. B-33) have published a review on the fracture toughness of the cryogenic nickel steels. Results are indicated in the following table of 95% confidence level lower bound K_c values:

-196°C	112 ksi $\sqrt{in}$
-170°C	150 ksi $\sqrt{in}$

Another extensive data collection (Rer. B-34) is available for both static and dynamic fracture toughness at -196°C for 1" thick plates. These are noted in Fig. B.15 and Fig. B.16. The mean values for both the static and dynamic case are above 100 ksi $\sqrt{in}$. These values are only conditionally valid, however, not meeting ASTM validity criteria. They do meet the value of $(K_{Ic}/\sigma_{ys})^2 = 1$, which has been suggested (Ref. B-35) as a validity criterion for lower-strength materials. The distribution of values noted from Figs. B.15 and B.16 shows 89% of the static, and 98% of the dynamic toughness values are above $K_{Ic} = 57$ ksi $\sqrt{in}$ at 196°C. At the temperatures encountered in the support structures, some 220 C° above these temperatures, no problem with brittle fracture is envisioned.

A-387D is a 2-1/4% Cr-1% Mo steel used for higher temperature applications. Because of the high temperature strength emphasis on this material, little fracture toughness data could be found at below ambient temperatures. Some data generated by the Clinch River Breeder Reactor project (Ref. B-36) indicates that NDT should be 20-30°F in the annealed condition. K_{Ic} from J_{Ic} (J_{Ic} is a proposed method for measuring fracture toughness in ductile materials. It has not yet been ASTM-standardized) values from this program measured at 75°F indicate very tough behavior under static conditions. Even after undergoing a temper embrittlement treatment values over 180 ksi $\sqrt{in}$. were obtained. Dynamic measurements of K_{Ic} were not reported. Sub-ambient K-data found indicated K_c (1") of 70 ksi $\sqrt{in}$ at -76°F, this particular heat (normalized and tempered) had an NDT of -10°F. Some French work (Ref. B-37) in 7" thick normalized and tempered material indicated a K_{Ic} of 45 ksi $\sqrt{in}$ @ -110°F. At -50°F a K_Q (ASTM invalid) value of 90 ksi $\sqrt{in}$ was obtained.

If the NDT values of 20-30°F for the as-rolled and -10°F for the normalized condition are indicative, this grade should behave similarly to A-302.

B.4.5 Quenched and Tempered Steels

Aside from the bolting grades, previously discussed, this category includes A-514, A-517, A-533 (a quenched and tempered variant of the A-302 type), A-537 (a quenched and tempered version of C/Mn steel, A-543 (otherwise known as HY-80), and A-508, a vacuum-treated Ni-Cr-Mo-V forging grade.

These steels have excellent fracture toughness, especially in the relatively thin sections encountered in the support structures (except for some thick A-508 forgings) when properly processed.

Maximum NDT values found are indicated in the following table:

Grade	Max NDT	Thickness	Source
A-508 Cl2	40°F	11"	ASME Task Force (Ref. B-38)
A-514	-10	2"	Hartbower (Ref. B-39)
A-517	-20		Eiber (Ref. B-40)
A-533 Gr B Cl1	20°F	8"	ASME Task Force
A537 Cl2	-60°F	2"	ASME Task Force
A543	-60°F		Structural Alloys Handbook (Ref. B-41)

The A-517 data presented here ignores the approximately 200°F value reported by Hartbower, et al. (Ref. B-39). However, that particular heat did not meet A-517 specifications because of an error in melt practice (Ref. B-42). The presence of such material, as well as the abnormally high NDT value of 100°F for A-572 material at North Anna are reminders of why impact testing requirements are necessary. The results of this survey are indicative of acceptable commercial practice. However, there is always a finite possibility that a bad heat of material can be obtained if screening procedures are not used.

K-type measurements are most readily available for A-508 and A-533 materials. Indeed, so much work has been done that it is difficult to present. Notable efforts in reducing large amounts of K-type data have been made by a PVRC/MPC task group (Ref. B-43). For our purposes, however, the simpler ASME reference curve shown in Fig. B.17 is adequate, as it has been shown to conservatively represent K_{Ic} values for many heats of A-533 and A-508. Using the Barsom shift, which for A-533 and A-508 is 145°F at 50 ksi yield strength, a K_{Ic} value at -70°F is equivalent to K_{Id} at 75°F, the minimum plant temperature chosen. For A-533, NDT is 10°F, thus -70°F is NDT -80°F on Fig. B.17. From the K_{Ic} reference curve this indicates a lower bound of 35 ksi $\sqrt{in}$.

For A-508, since NDT is 40°F, -70°F converts to NDT - 110°F, which yields about the same value of 35 ksi $\sqrt{in}$.

If one assumes that the K_{Ic} reference curves are more general and can be applied to the A-514/A-517 steels, their shift (at 100 ksi yield) is only 65°F and a value of K_{Ic} at 10°F corresponds to K_{Id} at 75°F. With NDT = -10°F, 10°F corresponds to NDT + 20°F, and a minimum K_{Id} = 65 ksi $\sqrt{in}$ results. Using the same assumption for A-543, a shift of 88°F is required (at 85 ksi yield), so K_{Ic} at -13°F is needed; 13°F corresponds to NDT + 47°F, and a minimum K_{Id} is = 95 ksi $\sqrt{in}$. Similarly for A-537, at 55 ksi yield, the shift is 132°F, requiring K_{Ic} at -57°F. This corresponds to NDT + 30°F, and a minimum value of K_{Id} at 75°F is = 55 ksi $\sqrt{in}$.

Literature values for A-533 (Ref. B-44) indicate K_{Id} at 75°F = 90 ksi $\sqrt{in}$. Extrapolation of HY80 data (Ref. B-45) to NDT + 50°F indicates K_{Id} of roughly 75 ksi $\sqrt{in}$. This was a straight line approximation and is probably too low; a slight curvature to the line would increase this to above 80 ksi $\sqrt{in}$.

NDT + 20°F for A-517 (Ref. B-44) corresponds to K_{Id} of above 110 ksi $\sqrt{in}$. Thus the lower bound estimates made using the K_{Ir} curve are not optimistic.

A-461 Gr 630, which was specified by H. B. Robinson, is actually a precipitation hardened stainless steel (17-4 PH) in the H 1025 condition. This heat treatment is expected to produce a K_{Ic} of approximately 100 ksi $\sqrt{in}$. (Ref. B-47, B-48)

B.5 Heat Affected Zones (HAZ)

The heat affected zone contains a gradient of microstructures resulting from different thermal cycles at different locations. The zone itself is often arbitrarily divided into two regions; that which has undergone the allotropic transformation, and that which has not reached the critical temperature for this reaction.

Depending upon whether or not the structure is to be stress-relieved or not, certain guidelines can be suggested as to whether the HAZ toughness will decrease or increase (Ref. B-49). For steels which are not to be post weld heat treated (PWHT) the main problems involve a) the low toughness of high hardness transformation products at lower heat inputs, b) the strain and/or quench aging which may occur, especially at the tip of any defect or notch, or c) the coarse grain size of non-martensitic microstructures at high heat inputs. Remedies for these are a) to attempt to minimize transformation to high hardness products, or to temper them with subsequent passes, b) to choose a steel which is not susceptible to strain aging (i.e., containing carbide and nitride formers such as Al, Ti, V or c) to minimize the extent of the grain-coarsened region by minimizing heat input or using a grain-refined steel which will narrow the grain-coarsened region, respectively.

If the structure is to be post weld heat treated, the first two problems tend to disappear because of the tempering process. The third will depend upon the steel itself and the type of microstructure that is developed. In alloy steels forming martensites and bainites, PWHT helps. However in plain carbon steels forming ferrite pearlite aggregates, PWHT doesn't help, but the reduction of residual stress is beneficial.

PWHT may cause problems in alloys which tend to precipitation harden (those containing Cr, V, Cu especially). Also, since stress relief treatments tend to involve long, slow cooling periods, temper embrittlement may become a problem. For plain carbon and fine grain practice carbon manganese steels in the post weld heat treated condition, the toughness of the HAZ should be about equivalent to that of the base plate (Ref. B-50) (see Figs. B.18, B.19). In HSLA steels, it has been noted that a rolling temperature which is too high will result in a high hardness, low toughness microstructure. In the grain coarsened region next to the fusion zone these excessive temperatures are encountered, and a low toughness region results. In this case PWHT serves to over age the precipitates, which allows the hardness to decrease and the toughness to increase. The toughness levels resulting would probably never recover to their original value, but would be characteristic of ordinary C/Mn steel. Some precipitates are difficult to over age, and short PWHT times may even cause further hardening and decreases in toughness.

In the low-alloy steels, martensite will form in the transformed HAZ, because of their relatively high alloy content. This martensite can be tough (C $\sim$ 0.1%) or brittle (C $\sim$ 0.2%) depending upon the carbon content present. Since the carbon is more likely to be around 0.2%, this martensite should be tempered by PWHT. In this condition, it should be as tough or tougher than the bainitic structure of the original plate. This is illustrated by the dramatic decrease in NDT of PWHT samples of A-302 compared with as welded (-50°F vs +55°F). (Ref. B-51) The carbon content is restricted in A-353 to 0.13% maximum, and the low carbon martensite present is tough. Multiple pass welding will serve to further temper and toughen this martensite. No PWHT is necessary. This data is shown in Fig. B.20.

In A-387, similar behavior to A-302 would be expected except for the presence of significant age hardening. This can be avoided by using a higher temperature PWHT, to over age the precipitate. The presence of the age hardening process may result in a phenomenon called stress relief cracking. The necessity for stress relief may not be present if the carbon content is low enough. The ASTM specification calls for a maximum of 0.15%. If this is not approached, the low-carbon martensite formed should be adequately tough.

The quenched and tempered grades of steel all would be expected to provide martensite or lower bainite in the HAZ. Indeed, procedures for welding some of these grades specify maximum heat inputs (A-514/A-517 in Ref. B-52, A-543 in Ref.B-53) in order to provide a fast enough cooling rate for the HAZ. Data for A-517 (Ref. B-54) in Fig. B.21 indicate that the HAZ toughness can be higher than that of the base plate (also in this figure is data for A-542, which is a Q&T version of A-387D. The HAZ toughness of the two would be expected to be very similar). Comparison of NDT values (Ref. B-55) for A-543 and the HAZ for various processes in Fig. B.22 indicate that again, it is possible to have a very tough HAZ. (In this figure BOND refers to HAZ). Data for A-508 (Ref. B-56) in Fig. B.23 indicate that its HAZ is at least as tough as the parent plate, and comparison of Fig. B.24 and Fig. B.25 indicates the same for A-533 (Ref. B-57). Both materials are in the stress-relieved condition. A 537 is a C-Mn-Si steel which has been given a quench and temper treatment, thus its hardenability would be expected to be considerably lower than the other materials in this category. For this reason its HAZ toughness may be closely approximated by A-516 data. Chemical specifications for A-516 fall within that for A-537, except for slightly higher carbon content. From Fig. B.22 it can be seen that the NDT value for A-516 Gr 70 is still about 0°F for high energy input (110 kJ/in) submerged arc welds. The lower carbon content in the A-537 should insure a lower NDT temperature. Apparently these data (and the A-543 data also) refer to the as-welded state.

To summarize the HAZ section, those materials that may be troublesome fall into two divisions.

As-welded state:

-- plain carbon and HSLA materials where strain-aging is not controlled with nitride-formers (troublesome only in the presence of a discontinuity or crack).

-- steels which produce high hardness low toughness microstructures.

Post weld heat-treated state:

-- steels containing age-hardening alloy additions.

-- steels susceptible to temper embrittlement.

Stress-relief cracking and temper embrittlement have been mentioned briefly. They are discussed, along with other metallurgical phenomena in section 4.5.

Table B.1
Sources of Data for Mild Steels

Reference	Material	Type of Data
Orner, Hartbower, Weld J. Res. Suppl. 40 (1961) p 459-S	WWII ship plate	NDT, PCC
Metals Handbook Vol I ASM	A-7	CVN
Cooley, Lange WRC, Nov 1967, p 1	A-212A	NDT, CVN, DT
ASME Task Group N-70-45	A-515, A-106	NDT
Gross Weld Res. Suppl. (1960) p 59-S	A-201A A-212B A-285C	NDT, CVN
Murphy, McMullen, Stout Weld Res. Suppl. (1957), p 307-S	A-7 A-201A A-212B A-285B	NDT, CVN
Eiber, personal communication	A-212B	NDT, DT, CVN
Zar, Goedjen Weld Res. Suppl (1961) p 371-S	A-7	CVN
Buck TM M-44-77-10 May 1977	A-515 A-106B	PCC, CVN, DT
Hodge MPC p 123	A-283 A-285	NDT, CVN (averages only)
Loginow, Phelps Corrosion-NACE (31), 1975, 404	A-106	K_Q (static)
Turner, Radon Fracture 1969 p 165	mild steel (English)	K_{Id}, NDT
Sunamoto, et al. Mit. Hvy Ind Tech Rev (12), 1975, p 71	mild steel (Japanese)	K_{Id}, NDT
Egan Eng. Frac. Mech. (J), 1973, p 167	mild steel (English)	K_Q, δ_c, J (static)

Table B.1 (continued)

Reference	Material	Type of Data
Kanazawa, et al. Jpn/Us Signif of Def. in Welded Structures, Proc., Tokyo, 1973, p 308	mild steels (Japanese)	δ_c, (static)
Otsuka, et al. ibid, p 242	mild steels	δ_c (static)
Nordell, Hall Weld Res. Suppl. (44), 1965, p 124-S	A-212B	K_{arrest}
Chow, Owen J Strain Anal. (11), 1976, p 195	mild steel (English)	G_c (static)
Robinson Int. J. Fract. (12), 1976, p 723	mild steel (English)	δ_c (static)
Ripling ASTM STP 559 p 59	1020 CW	K_{Ic}, K_Q, CVN
Burns, Bilek Met. Trans., (4), 1973, p 975	1020	K_{Id} (dynamic)
Kanazawa Fract [illegible] 1969 p 1	mild steel (Japanese)	δ_c (static)
Ritchie, Knott J Mech. Phys. Sol. (21), 1973, p 395	mild steel (English)	K_{Ic} (static)
Radon, Turner JISI, 1966, p 842	mild steel	K_{Id}
Roberts, et al., FHWA-RD-74-59 Sept 74	A-7	K_c, K_d, DT, CVN
GEAP-5637 (1968)	A-106B	K_c (static)
Priest Dyn Frac Tough The Welding Inst 1977, p 95	mild steel (British)	K_{Id}

Table B.2
Sources of Data for C-Mn Steels

Reference	Material	Type of Data
Roberts, et al., FHWA-RD-74-59 1974	A-36	K_c, K_d, CVN, DT
North Anna "Affair"	A-36	CVN, NDT
Barsom, et al.	A-36	K_{Ic}, CVN, DT
Staugaitis SSC 106, 1958	ABS-B, C	NDT, CVN
ASME Task Group N-70-45	A-36, A-105, A-516, A-537,	NDT
Hodge MPC	A-36, ABS-A, B A-516, A-537	CVN, NDT
Banks Weld J. Res. Suppl 1974, p 299-S	A-36 like (Australian)	K_{Ic}, K_{Id}, CVN
McDonald 1977 ASTM Symposium preprint	A-36	K_c (static)
Zar, Goedjen Weld, Res. Suppl 1961, p 371-S	A-131B	CVN
Turner, Radon Fracture 1969 p 165	C/Mn	$K_{Iarrest}$
Rothman, et al., N00014-71-C-5088 1973	ABS-B, C	CVN
Hawthorne, et al., NRL-7701, 1974	ABS-A, B, C, D, E, CS	NDT, DT, CVN
Orner, Hartbower Weld, Res. Suppl 1961, p 459-S	C/Mn, ABSC	NDT, CVN
Brunet, et al. Rev. de Met. 1977, p 1	C/Mn (French)	CVN
Fegredo Can Met Quart. 1975, p 243	C/Mn (Canadian)	K_Q

Table B.2 (continued)

Reference	Material	Type of Data
Kuang, VonRosenburg O.T.C. Preprint 1974	ABS-C, CN, CS, D A-36, A-537	NDT, CVN
Shoemaker, Rolfe Eng Frac Mech 1971, p 319	ABS-C	K_{Ic}, K_{Id}, DT, CVN
Loginow, Phelps Corrosion-NACE 1975, p 404	A-516	K_Q
Eiber, personal communication BMI	A-516	NDT, DT, CVN
Otsuka, Miyata Proc Signif of Delects in Welded Struc., Tokyo, 1973	C-Mn (Japanese)	δ_c
Sunamoto, et al., Mitsubishi Hvy Ind Tech Rev, 1975, p 71	C-Mn (Japanese)	K_c, K_{Id}, NDT
Kanazawa, et al., Fracture 1969 p 1	C/Mn (Japanese)	δ_c

Table B.3
Sources of Data for High Strength Low Alloy Steels

Reference	Material	Type of Data
Roberts, et. al. (Lehigh) FHWA RD 74 59 (1974)	A-441, A-588B	K_c, DT, CVN
Novak, ASTM STP 591 (1974)	A-572	K_c (R-curve)
North Anna "affair"	A-572	K_{Ic}, CVN, ND'
Hodge, MPC	A-441, A-572	NDT, CVN
MacDonald, 1977 ASTM Seminar, Preprint	A-572, A-588	K_Q
E. Banks	A-441	COD, CVN
Barsom, et al.	A-572	K_{Ic}, CVN, DT
Kuang and Von Rosenberg	A-572	CVN, NDT
Rothman, Monroe SSC-235	A-441	CVN
M. E. Seuss, T. L. Proft SAE Trans. Sect. 3, 1976 p 2061	A-572	CVN, NDT

Table B.4
Sources of Data for Low Alloy (Non Quenched and Tempered) Steels

Reference	Material	Type of Data
Shoemaker and Rolfe Engrg. Frac. Mech. (1971) p 319	A-302B	K_{Ic}, K_{Id}
Gross, Weld. J. Res. Supp. (1960), p 59-S	A-302B	CVN, NDT
USS Low Temp. and Cryogenic Steels, Mat'ls. Manual, p 55	A-353	CVN
Tenge, Karlsen, Mauritzon Int. Conf. on Dynamic Fracture Toughness, London (1976), p 195	A-353	K_{Ic}, K_{Id}
Seman, Kallenberg, Towner WAPD-TM-895 (1971)	A-302B	K_{Ic}, K_{Id}, NDT
Pense, WRC Bulletin 205	A-353	
Donati, Valibus, Zacharie Weld Res. Related to Power Plant, (1972)	A-387D	CVN
Wullaert, et al. Frac. Toughness Data for Ferritic Nucl. P.V. Mat'ls. (1976) EPRI NP 121	A-302	K_{Ic}, NDT, CVN
Tvrdy, et al. 3rd Intl. Conf. on P.V. Tech. (1977), p 613	A-353	K_c, K_d
GEAP-142029-8	A-387	K_{Ic}, NDT
Wessel, Clark, Wilson 1966 ATAC Report	A-302B	K_{Ic}
Marandet, Sanz Centre de Documentation Siderurgique, Circulaire Informations Techniques, 33, 1976, p 2231	A-387	K_{Ic}

Table B.5
Sources of Data for Quenched and Tempered Steels

Reference	Material	Type of Data
Fracture Toughness Data for Ferritic Nuclear P.V. Mat'ls. EPRI/NP-121 (1976)	A-508 A-533 A-302 & weldments	K_{Ic}, NDT, CVN
Rothman, Monroe SSC-235 (1973)	A-537	CVN
Hodge, WRC Bulletin 217 (1976)	A-533 A-508 A-543	CVN, NDT
J. H. Gross WRC Bulletin 147 (1970)	A-517F	CVN
Frac. Toughness of High Strength Bridge Steels CA-DOT-TL-6593-1-74-20 (1974)	A-514/A-517	K_Q, CVN
F. J. Loss, J. of Eng. for Ind. (1973), p 139	A-517 A-533	
Rolfe and Novak ASTM STP 466 p 124 (1970)	A-517	CVN, K_{Ic}
Barsom, J. of Eng. for Ind. (1971), p 1209	A-517, A-543	K_{Ic}
Crosley, Ripling Nucl. Eng. & Design (1971), p 32	A-533	K_{Ia}
Miyamoto, et al. 2nd I C Mech. Beh. of Mat'ls. (1976), p 1063	A-533	J_{Ic}
PVRC/MPC Task Group on Fracture Toughness Props Mech. Components Final Report (1977)	A-508 A-533	K_{Id}
Sunamoto, et al. Mitsubishi Hvy. Ind. Tech. Rev. (1975), p 71	A-543	K_{Id}, NDT, DT
R. J. Eiber Personal Comm.	T-1A	NDT, CVN

Table B.5 (continued)

Loginow & Phelps Corrosion NACE (1975), p 404	A-517F	K_{IX}
Kuang, Von Rosenberg OTC Paper 1953 IEEE 1974 Offshore Tech.	A-537	NDT, CVN
H. Kunitake, et al. 3rd Int. Conf. on P.V. Tech. (1977), p 603	A-533B	NDT, CVN
Ikeda, et al. Ibid, p 647	A-508	K_{Ic}
Susukida, et al. Ibid, p 619	A-543	K_{Ic}
Seman, Kallenberg, Towner WAPD-TM-895 (1971)	A-508	K_{Ic}, K_{Id}, NDT

Table B.6
Sources of Data for Cast Steels

Reference	Material	Type of Data
Steel Founders Soc. of Am. personal communcation	A-27, A-216 A-148, A-352	NDT, CVN, DT
Greenberg, Clark Metals Eng. Quant. 1969, p 30	A-216	K_{Ic}
Banks, et al. JPV Tech., Trans. ASME 1974, p 73	A-216	NDT, CVN
Barnby, Al-Daimalani J. Mat'ls. Sci. (11), 1976, p 1989	C, C-Mn (English)	K_c, J_{Ic}
Landes, Begley ASTM STP 560, p 170	A-216	K_{Ic}, J_{Ic}
Clark, Wessel ASTM STP 463, p 160	A-216	K_{Ic}

Table B.7
Sources of Data for Weld Metals (& HAZ)

Reference	Material	Type of Data
Dawes Weld & Met. Fabr. (40), 1972, p 95	MMA, SA ESA, FCA	δ_s
Dorschu, Stout Weld Res. Suppl 1961, p 97-S	SA, GMA	CVN
Dorschu WRC Bulletin 231, 1977	all	CVN
Hopkins, et al. Weld & Met. Fabr. (33), 1965, p 216	MMA, SA	CVN
Tait, Haddrill Weld & Met. Fabr. (38), 1970, p 370	MMA	δ_c
Tuliani, et al. Weld & Met. Fabr. (37), 1969, p 327	SA	CVN
Dolby Weld Inst. Res. Rpt. 11/1976/M 14/1976/M	all	δ_c
Toughness of Weld HAZ Weld Inst. Cambridge 1975	all	δ_c
Gittos, Dolby Weld Inst. Res. Rpt. 15/1976/M	MIG	δ_c
Robinson Weld Inst. Res. Rpt. 41/1977/M	MMA	δ_c
Pense FHWA-RD-76-109	ES, SA, MMA	
Herbert Proc. 2nd Conf. Signifc. of Defects in Welds, Weld Inst., Cambridge, 1969	SA	NDT

Table B.7 (continued)

Kimura, et al. 11W Annual Assembly 1967	MMA	CVN
Steele Mat'ls. Tech (1) p 414	SA, ES	CVN
Farrar Weld & Mat'l. Fabr. (44), 1976, p 578	all	CVN
Muncner, et al. Eng. Frac. Mech. (4), 1972) p 695	ES	δ_c
Masubuchi, et al. WRC Bulletin 111 1966	all	CVN
Susukida, et al. Third Conf. on P.V. Tech. Part II, Tokyo, 1977, p 619	MMA, SA, MIG	NDT, K_{Ic}
Ikeda, et al. Ibid, p 647	SAW	K_c, δ_c

Table B.9
K-Type Data for A-302B

Source	K_{Id}	K_{Ic}
Shoemaker, Rolfe 1", NDT = 20F, σ = 56 ksi	extrapolated 60 ksi $\sqrt{in}$ @ 60F	extrapolated 75 ksi $\sqrt{in}$ @ -70F
Seman, Kallenberg, Towner 7" norm. from center of plate		45 ksi $\sqrt{in}$ -100F
8 3/8" Q&T 1/4 thickness position		40 ksi $\sqrt{in}$ @ -100F
4" N&T 60 ksi yield		30 ksi $\sqrt{in}$ @ -60F
4" Q&T 60 ksi yield		45 ksi $\sqrt{in}$ @ -60F
7" Annealed	45 ksi $\sqrt{in}$ @ 60F	
7" N&T	extrapolated 45 ksi $\sqrt{in}$ @ 60F	
Wullaert, et al. EPRI NP 121 (1976)		
4" Q&T	128 ksi $\sqrt{in}$ @ 50F	60 ksi $\sqrt{in}$ @ - 50F
Wessel, Clark, Wilson 1966 ATAC Report		
7" Norm		49 ksi $\sqrt{in}$ @ -85F 37 ksi $\sqrt{in}$ @ -100F
7" Annealed		30 ksi $\sqrt{in}$ @ -100F

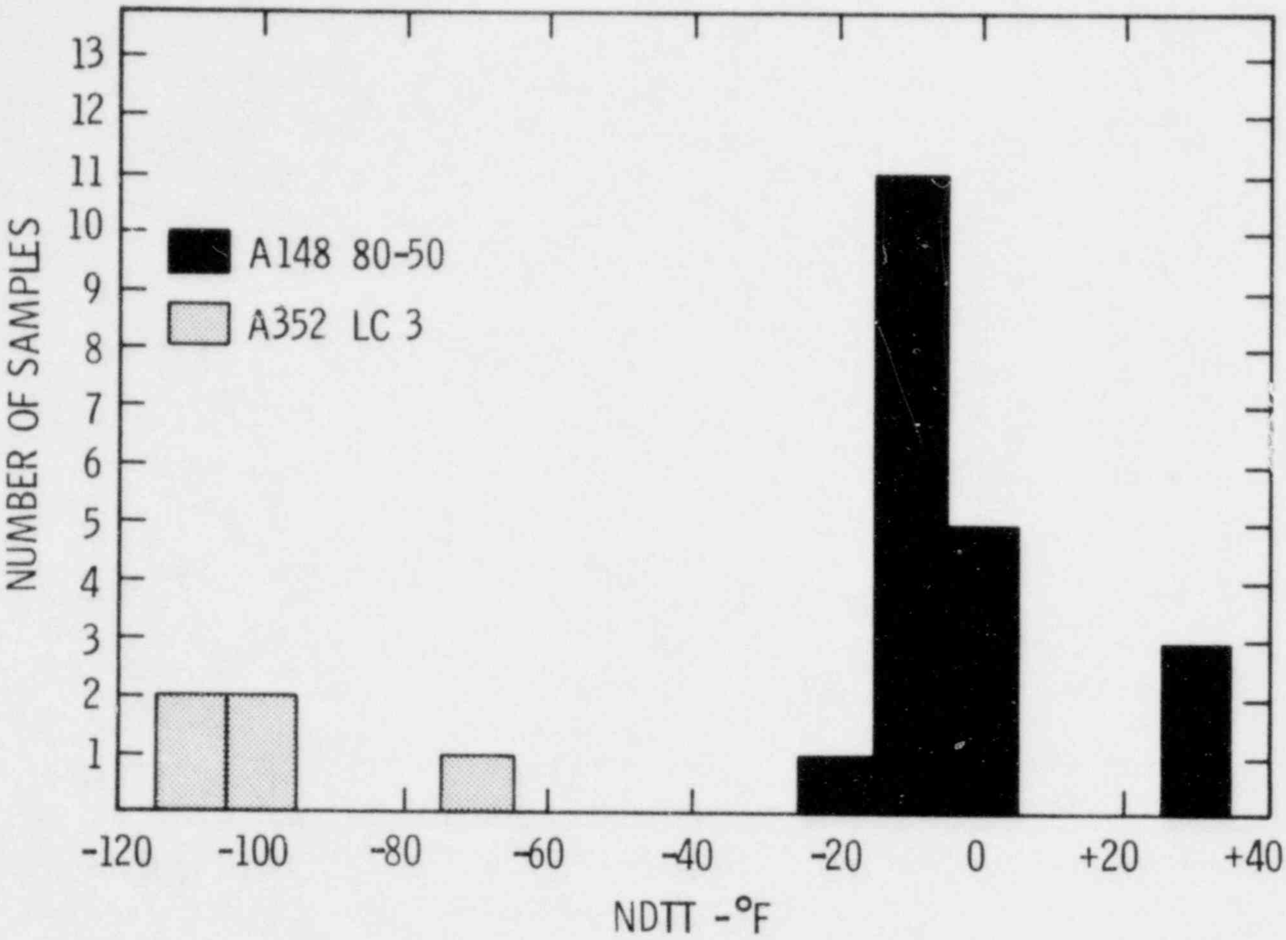
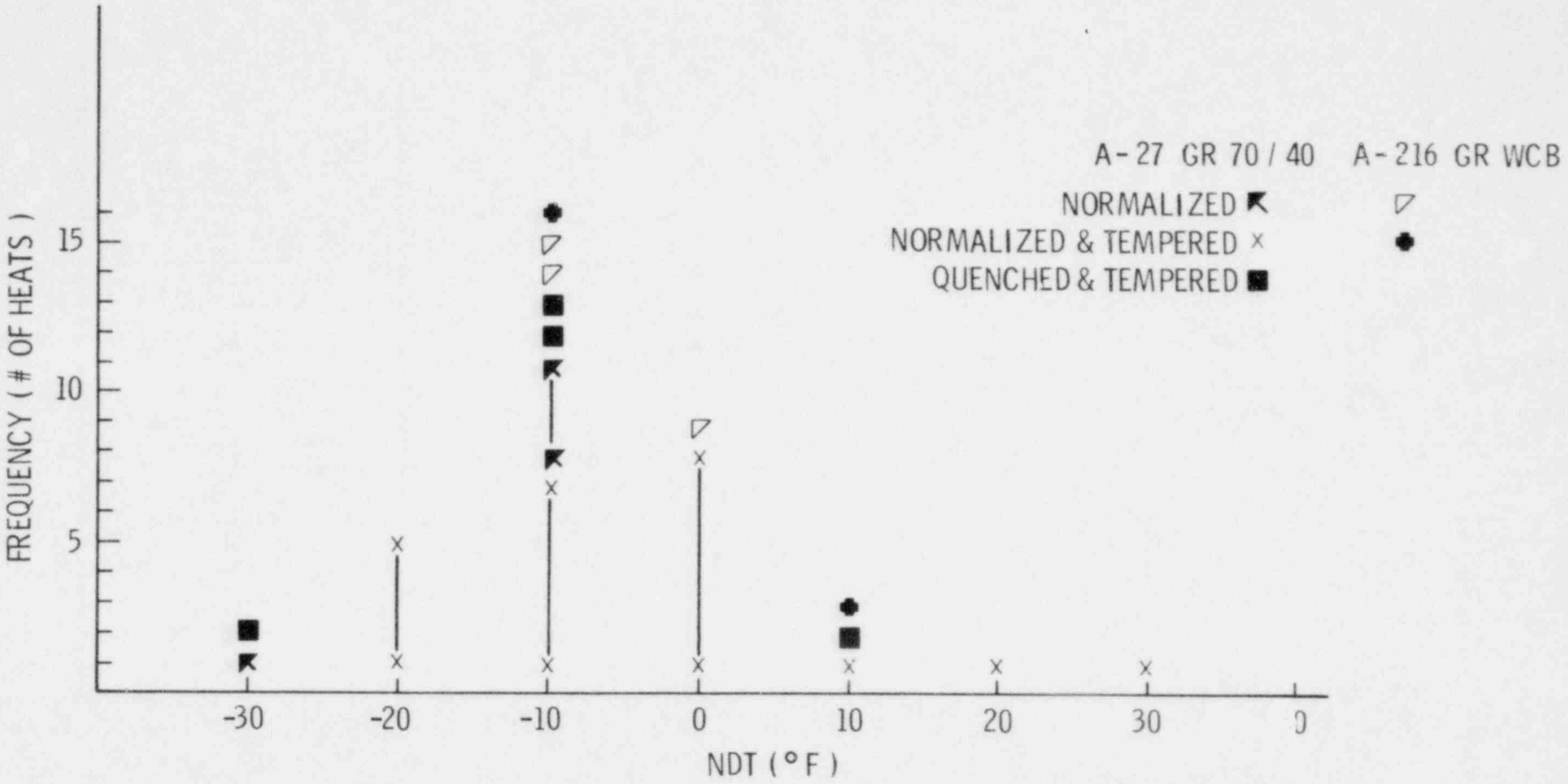
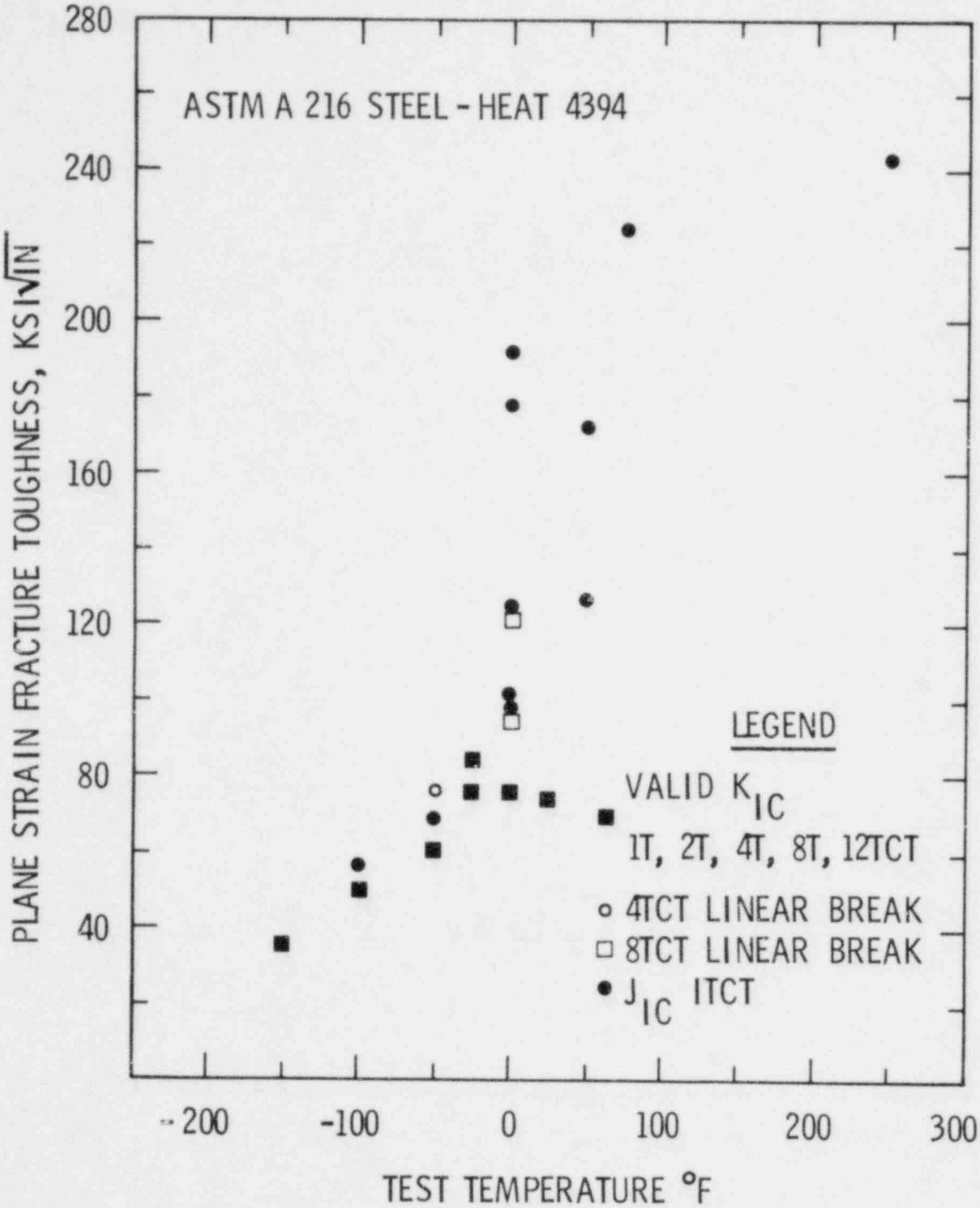


FIGURE B.1 THE NDTT DISTRIBUTION FOR NORMALIZED AND TEMPERED NICKEL STEELS.

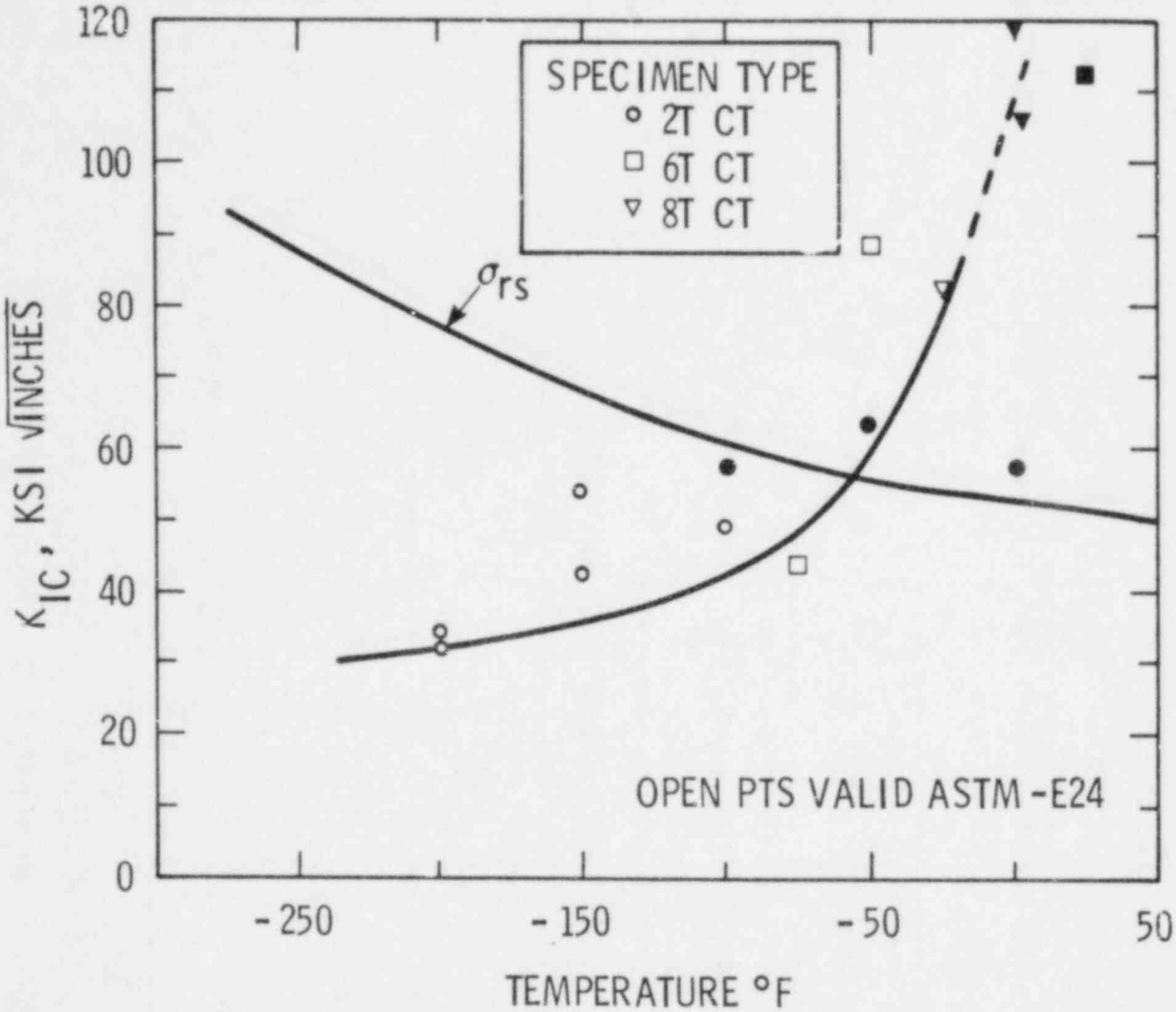
FIG. B.2 NDT FOR CAST GRADES
⟨NDT⟩ FOR A-27 IS -7 °F
σ " 13 °F





- FRACTURE TOUGHNESS VERSUS TEST TEMPERATURE

FIGURE B.3(a) A-216 K_{IC} DATA



TEMPERATURE DEPENDENCE OF YIELD STRENGTH AND K_{IC} FRACTURE TOUGHNESS FOR AN A216 (WCC GRADE) STEEL CASTING.

FIGURE B.3(b) A-216 K_{IC} DATA

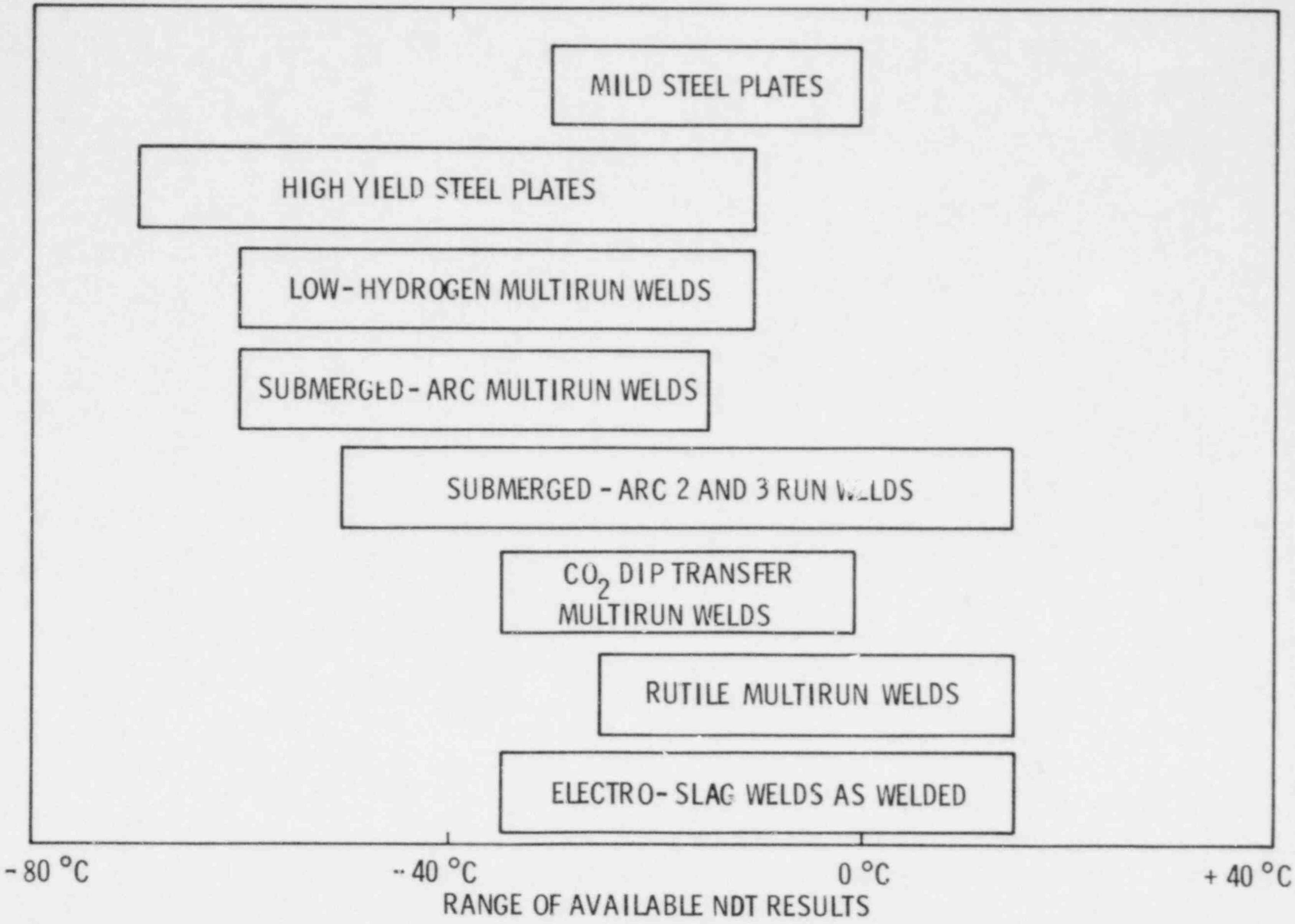


FIG B. 4 AUSTRALIAN WELD DATA NDT'S

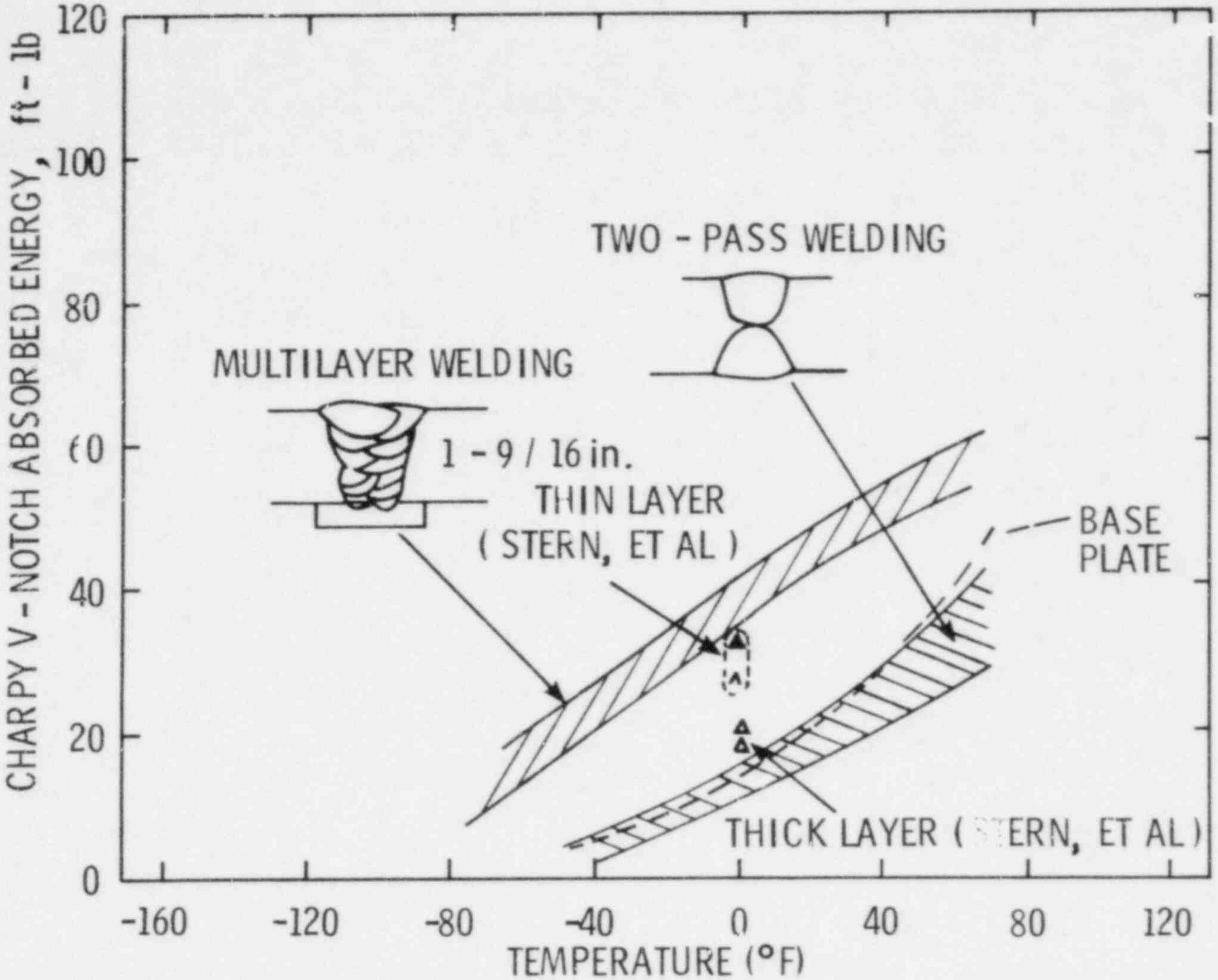


FIG. B.5 - NOTCH TOUGHNESS OF SUBMERGED- ARC WELD METALS, TWO-PASS AND MULTILAYER WELDING (AUGLAND, CHRISTENSEN

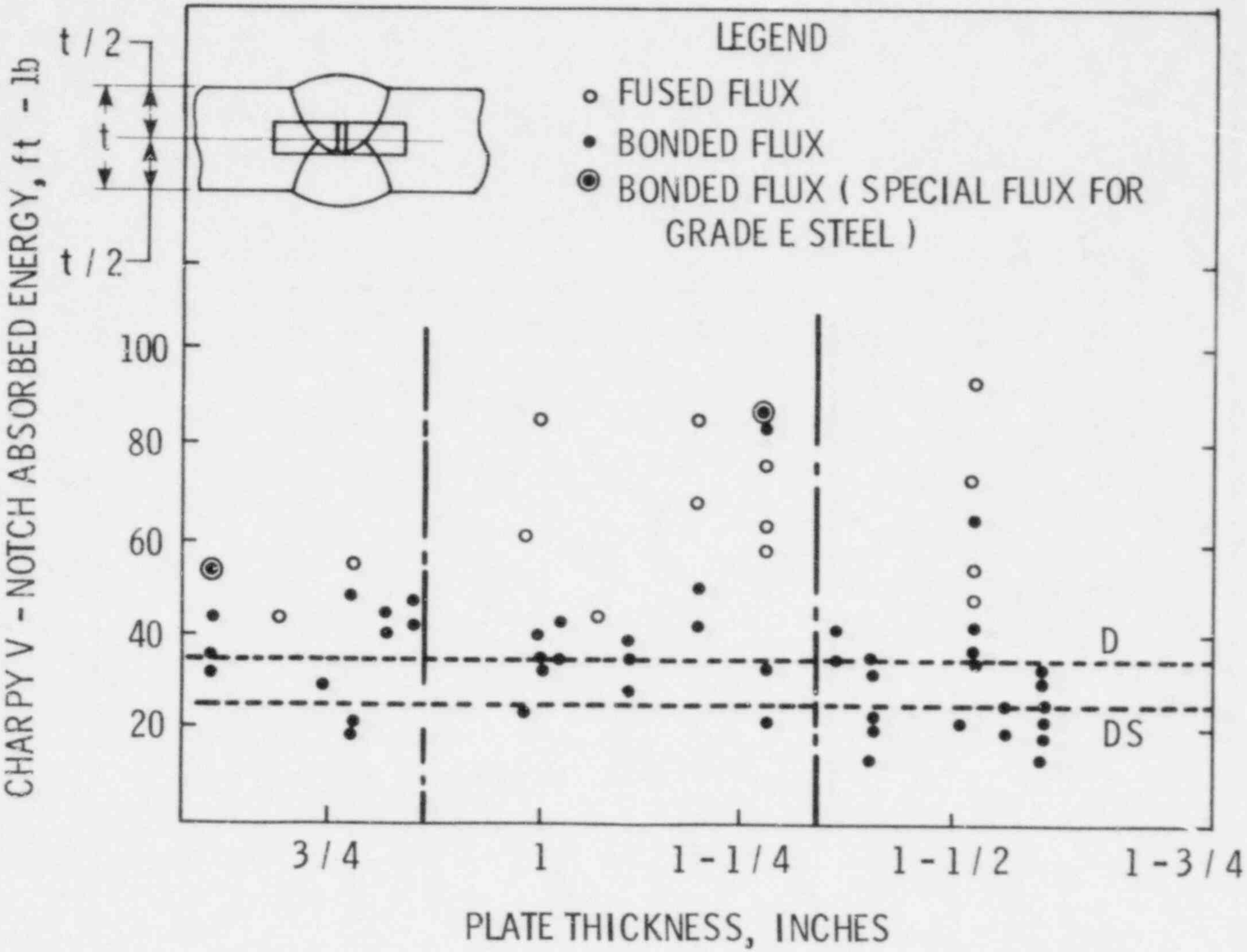


FIG. B.6 - VALUES OF ABSORBED ENERGY AT 32 °F OF CHARPY V -NOTCH IMPACT -TEST SPECIMENS TAKEN FROM MANY TWO - PASS SUBMERGED ARC WELD METALS OF STEELS OF VARIOUS THICKNESS (DATA ARE SUPPLIED BY MR. S. KAKU OF THE NIPPON KAIJI KYOKAI)

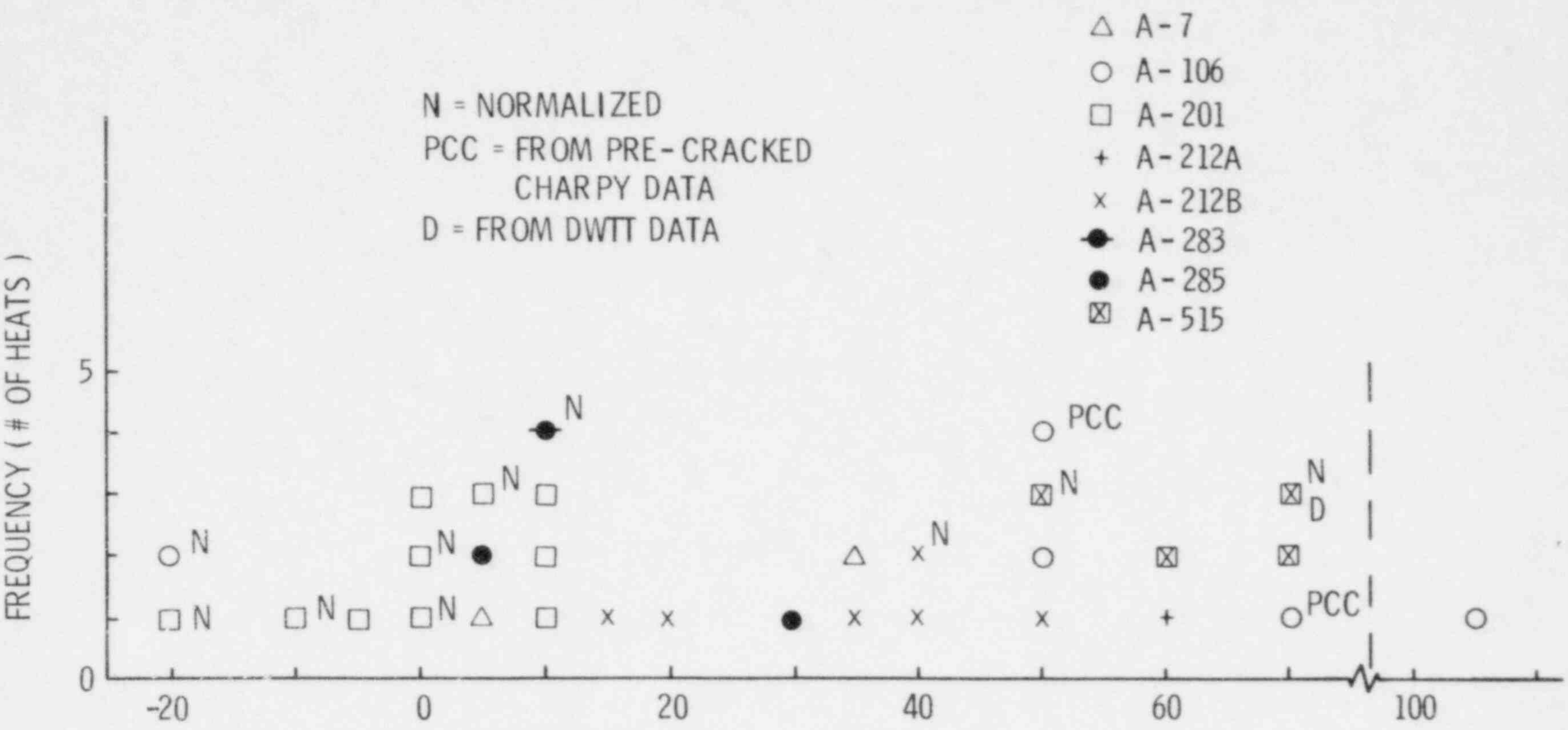


FIG. B.7 NDT VALUES FOR "MILD STEELS"

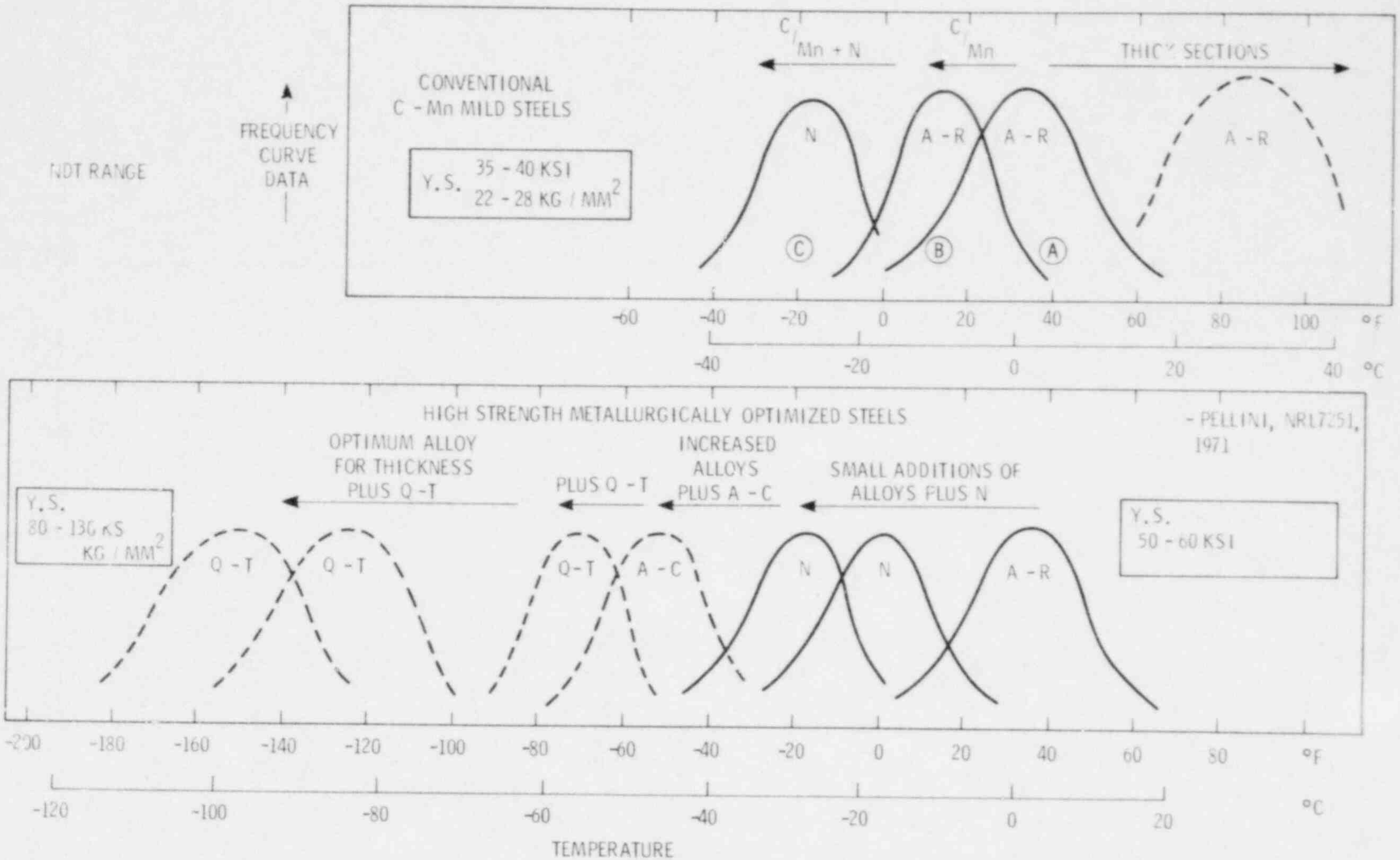


FIG. B.8 - REPRESENTATIVE NDT FREQUENCY DISTRIBUTIONS OF COMMF CIAL STRUCTURA STEELS. THE FIGURE NOTATIONS RELATE TO ALLOY CONTENTS AND HEAT TREATMENT FACTORS AS FOLLOWS: <C / Mn, DECREASED C TO Mn RATIO; A - R, AS ROLLED; N, NORMALIZED; A - C, ACCELERATED COOLING; AND Q - T, QUENCHED AND EMPERED.

FIG. B.9 FRACTURE TOUGHNESS DATA FOR "MILD STEELS"

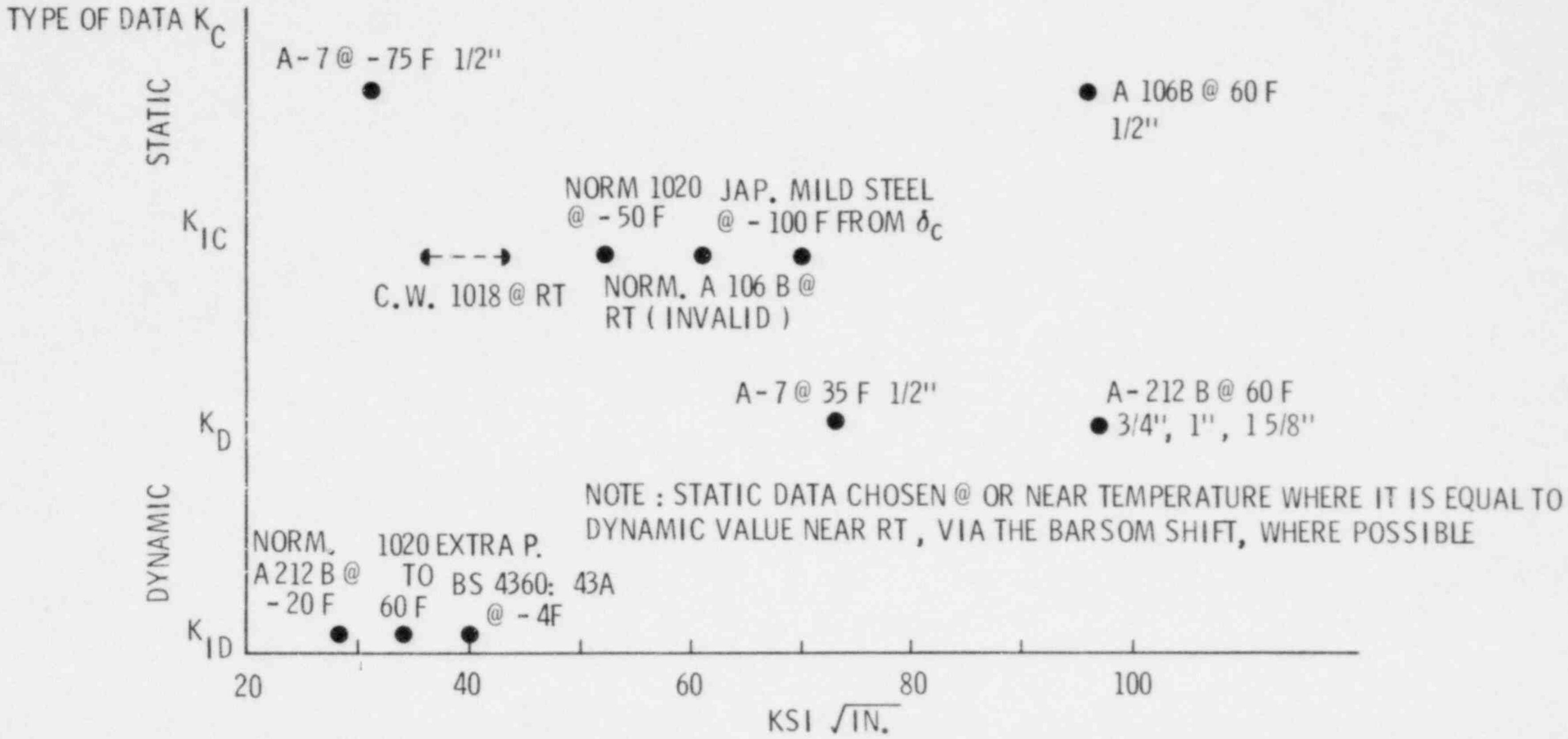


FIG. B.10 NDT VALUES FOR NORMALIZED C-MN STEELS

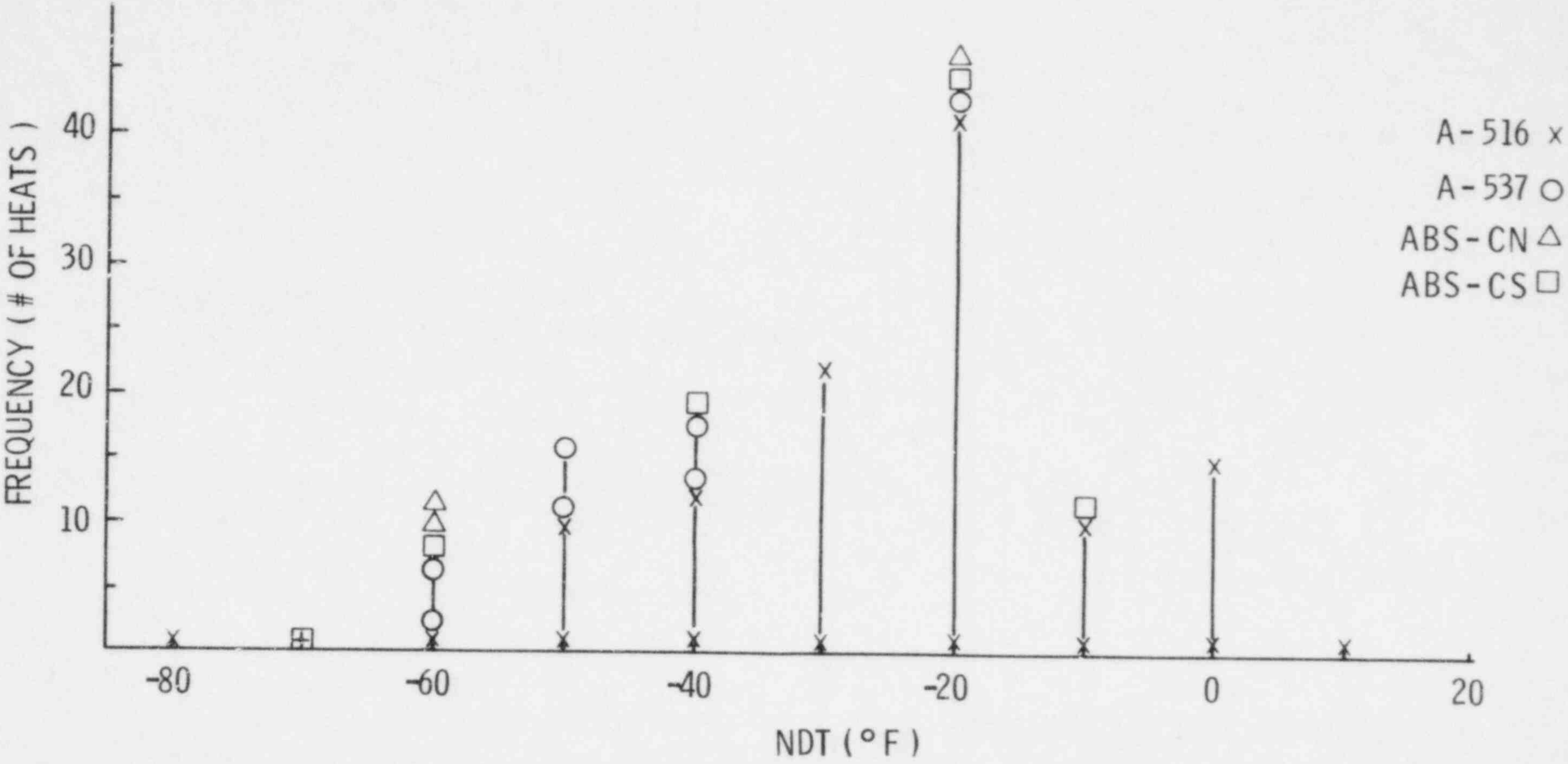


FIG. B.11 NDT VALUES FOR AS-ROLLED C-MN STEELS

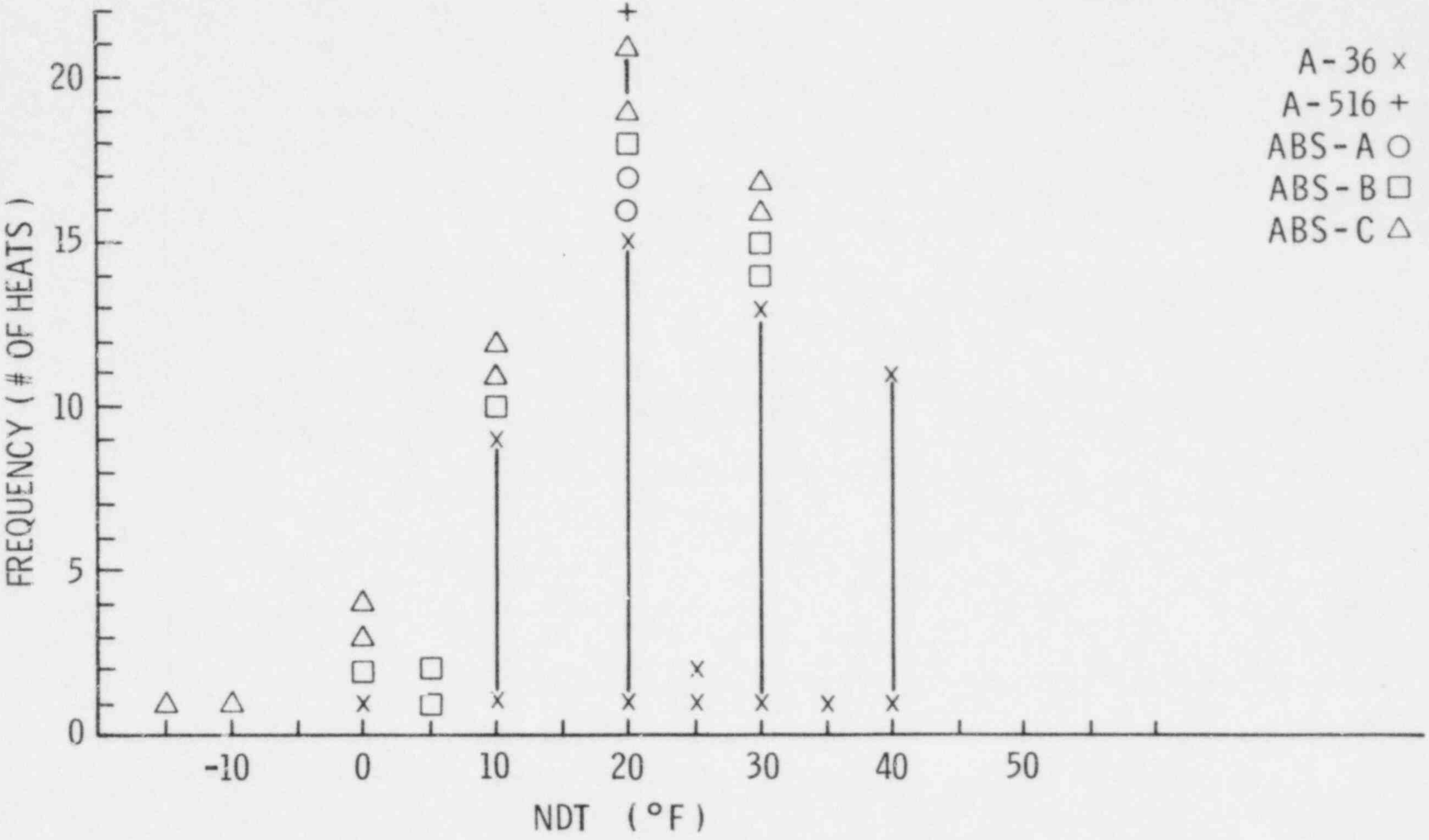
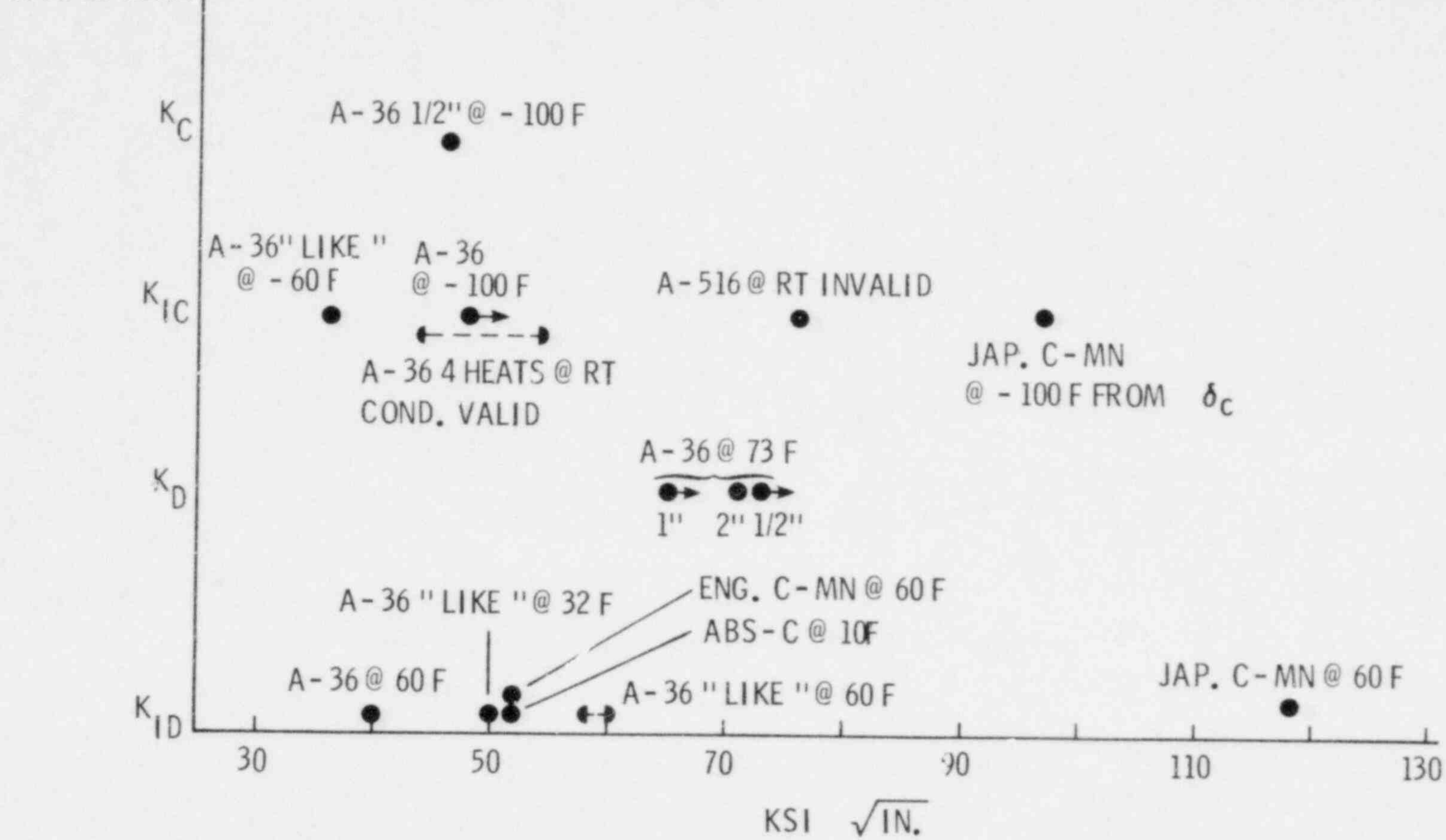


FIG. B.12 FRACTURE TOUGHNESS DATA FOR C-MN STEELS

NOTE : STATIC DATA CHOSEN @ OR NEAR TEMPERATURE WHERE IT IS EQUAL TO DYNAMIC VALUE NEAR RT, VIA THE BARSOM SHIFT, WHERE POSSIBLE



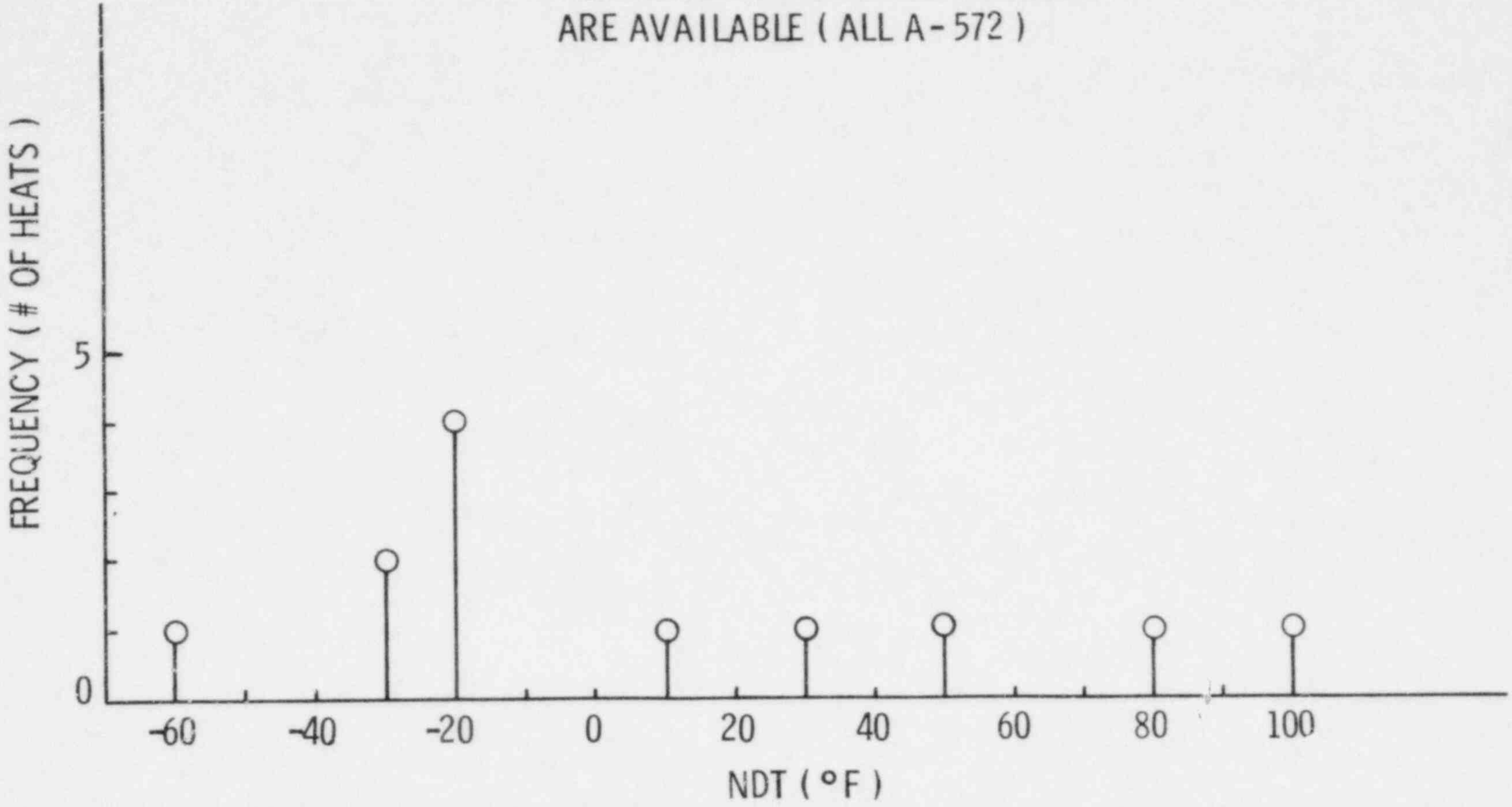


FIGURE FIG. B.13 NDT VALUES FOR HSLA STEELS FOR WHICH INDIVIDUAL POINTS ARE AVAILABLE (ALL A-572)

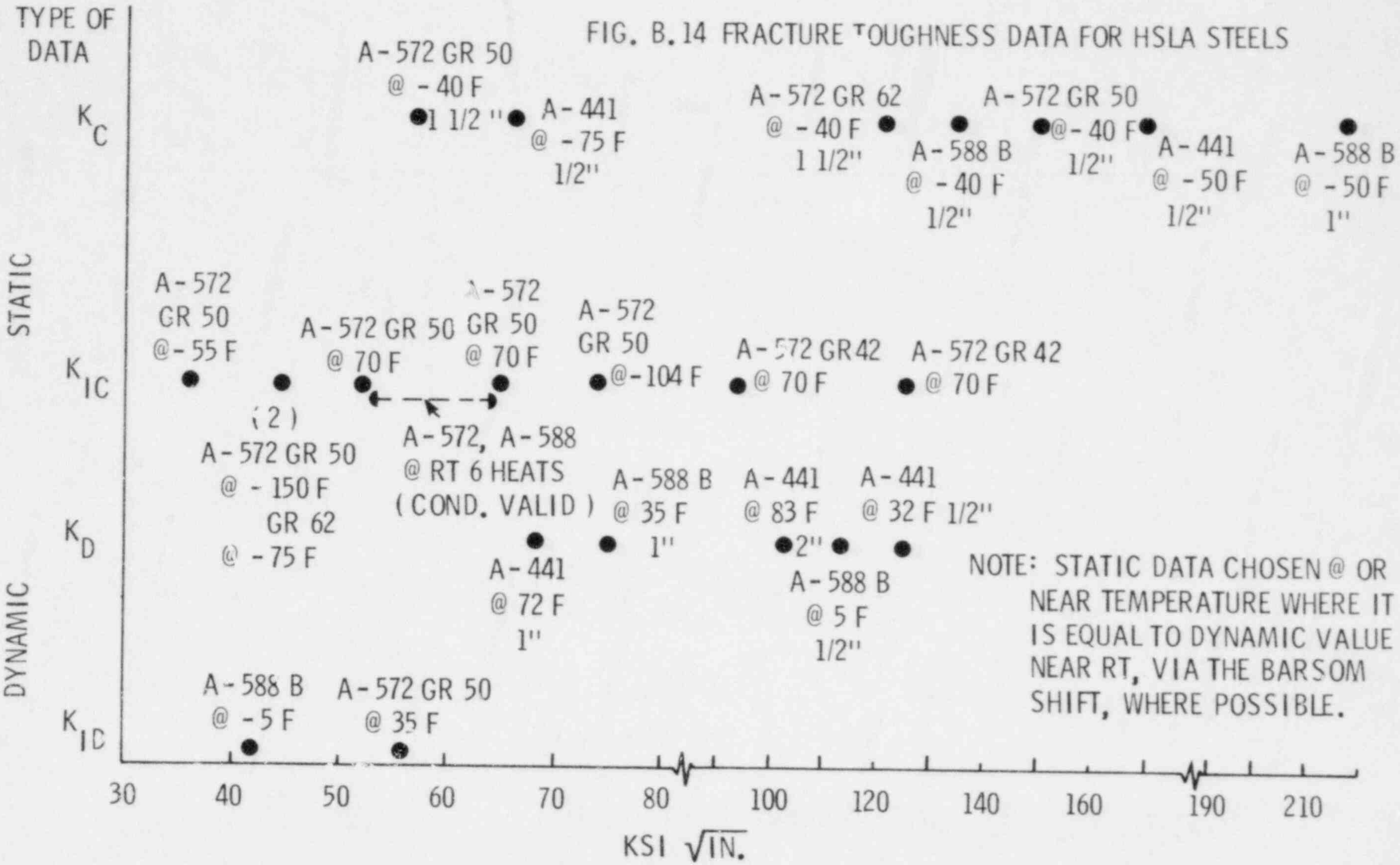
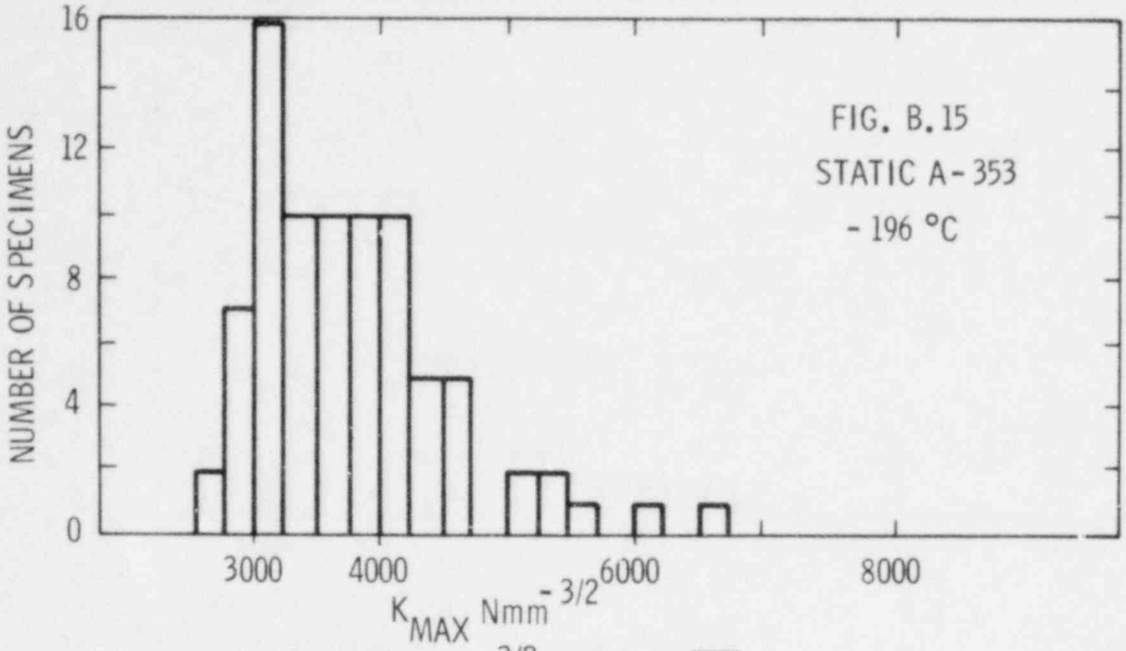
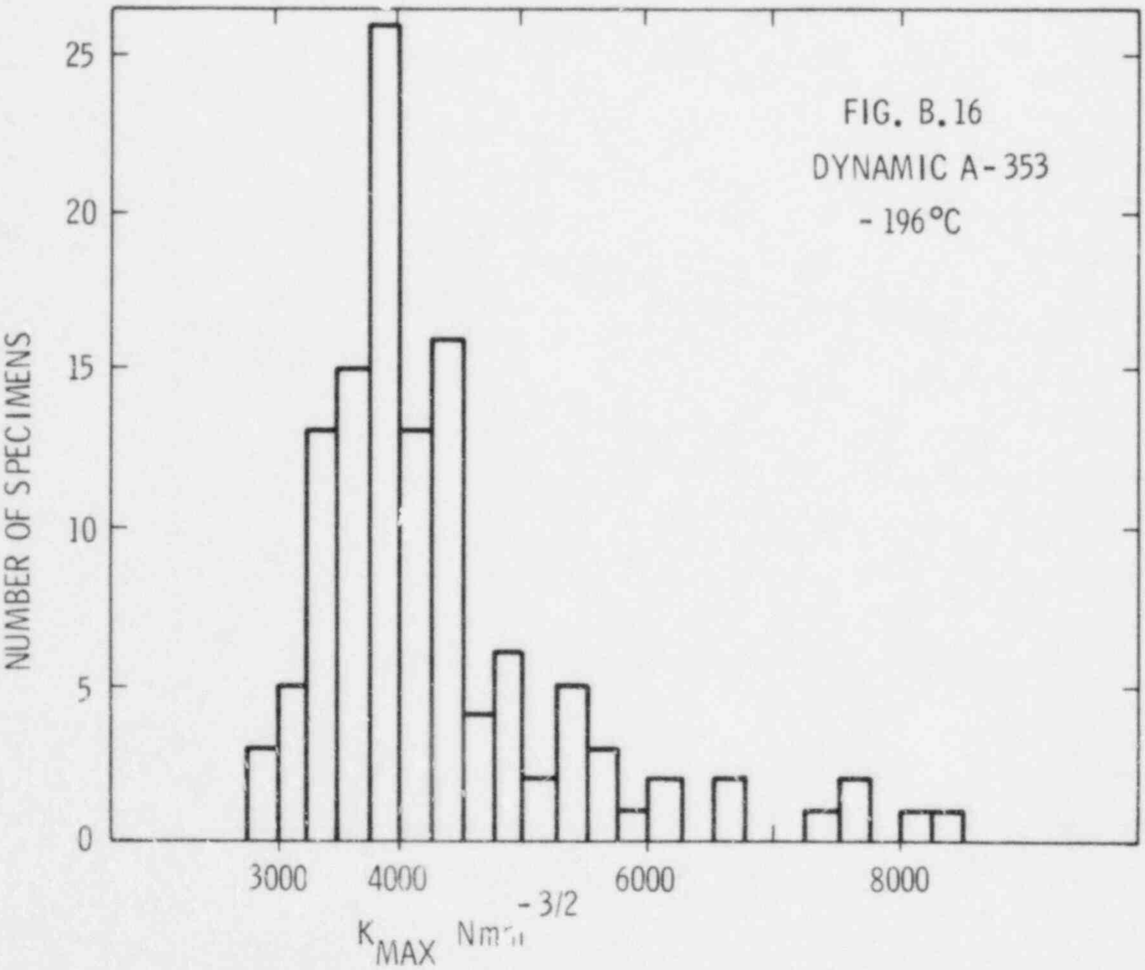


FIG. B.14 FRACTURE TOUGHNESS DATA FOR HSLA STEELS



NOTE: 3000 $Nmm^{-3/2}$ = 86 KSI $\sqrt{IN.}$



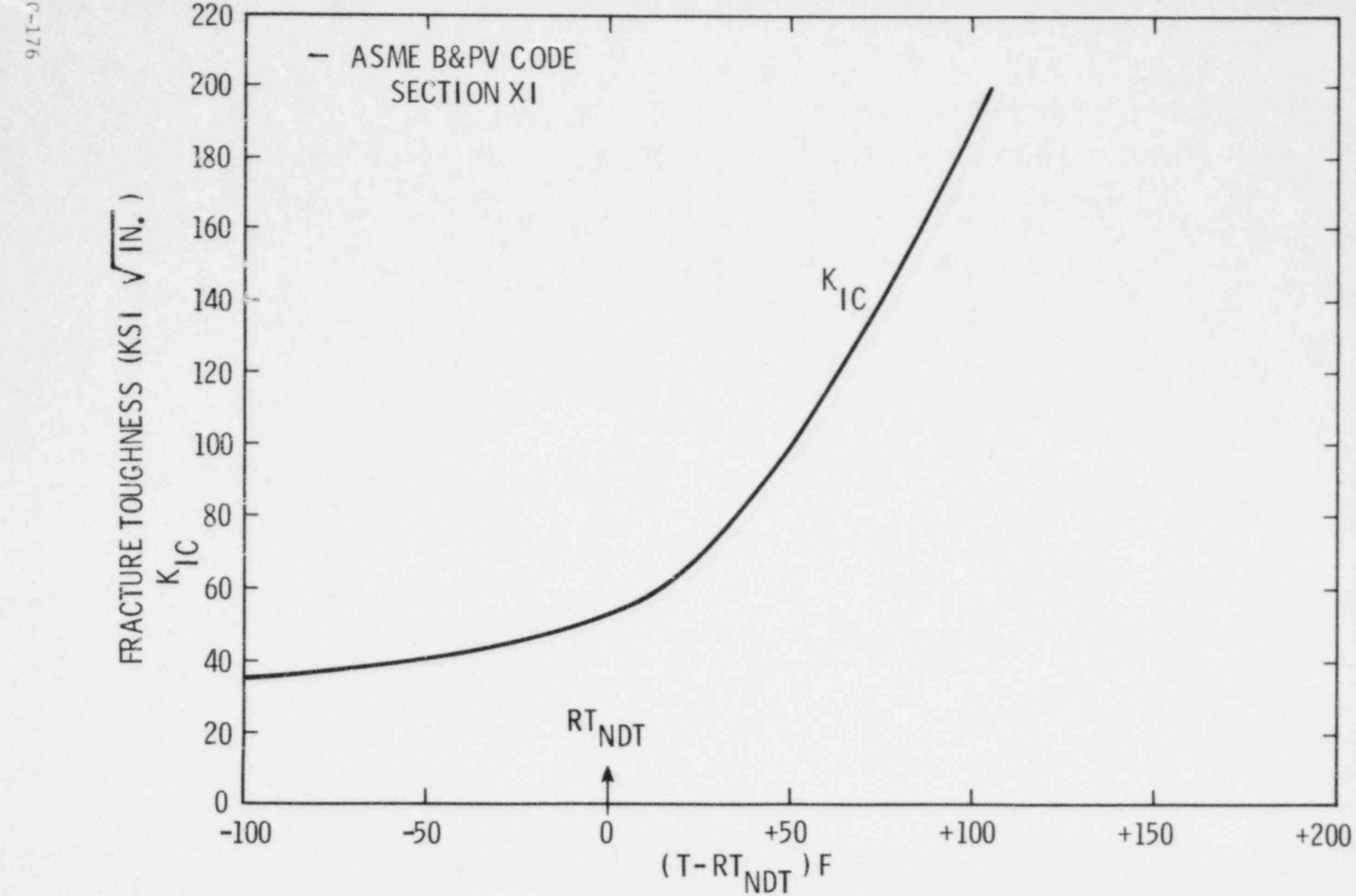


FIG. B.17 LOWER BOUND K_{IC} TEST DATA FOR SA-533 GRADE B CLASS 1, SA-508 CLASS 2, AND SA-508 CLASS 3 STEELS

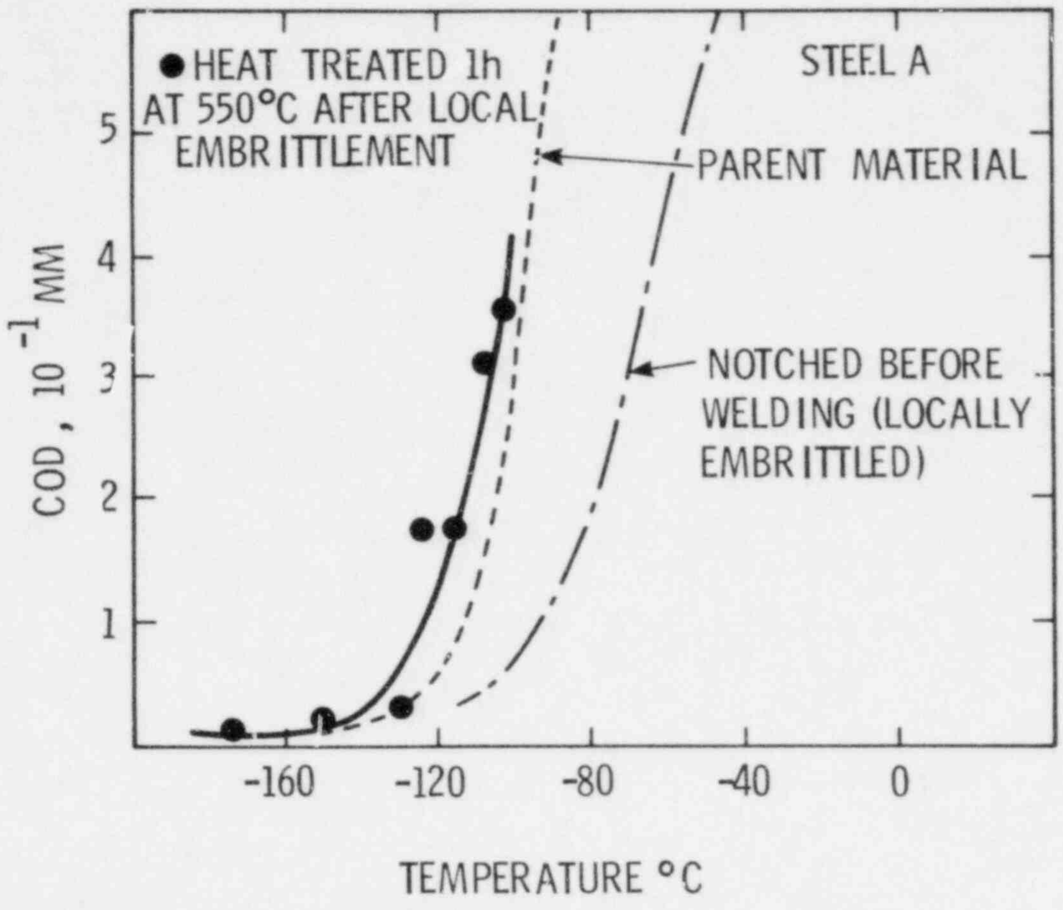


FIG. B.18 COD TRANSITION CURVES OF LOCALLY EMBRITTLED STEEL A WITH AND WITHOUT A POST-WELD HEAT TREATMENT OF 1h AT 550°C

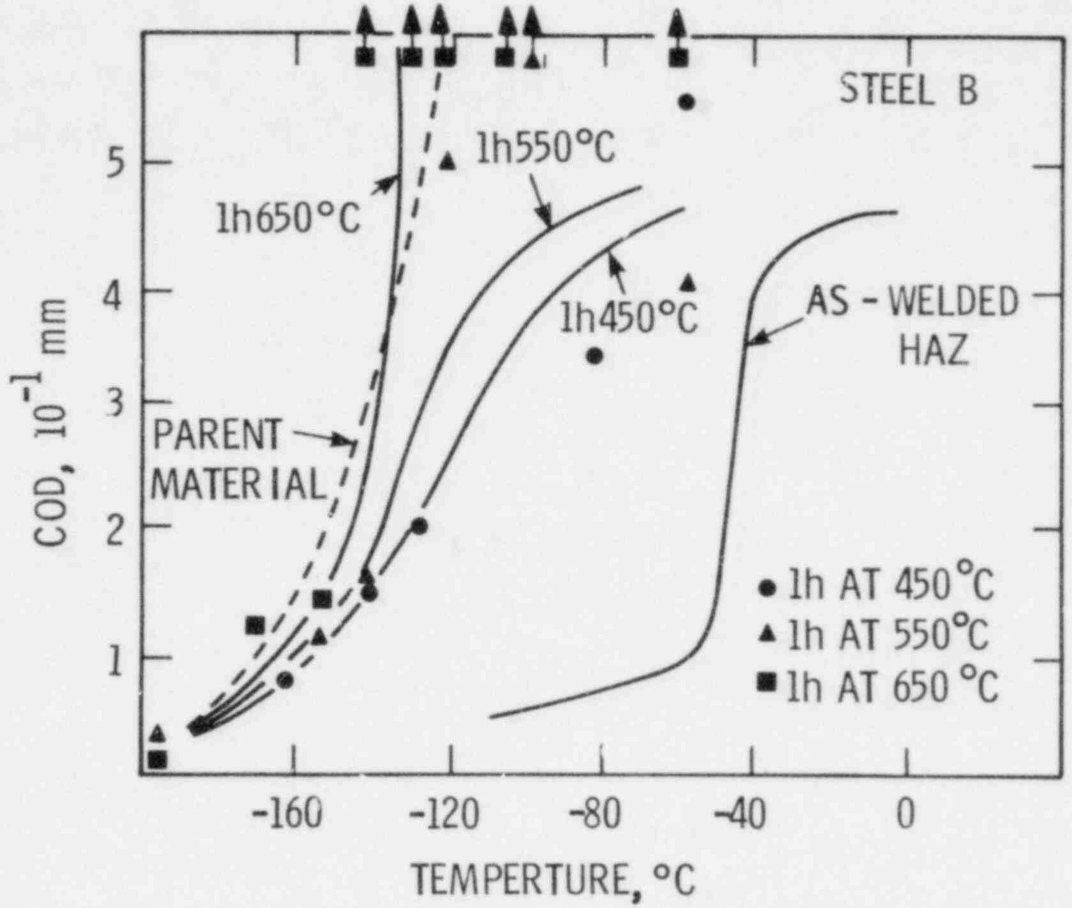


FIG. B.19 COD TRANSITION CURVES OF THE GRAIN -COARSENED HAZ OF STEEL B AFTER HEAT TREATMENTS FOR 1 h AT 450, 550, AND 650°C

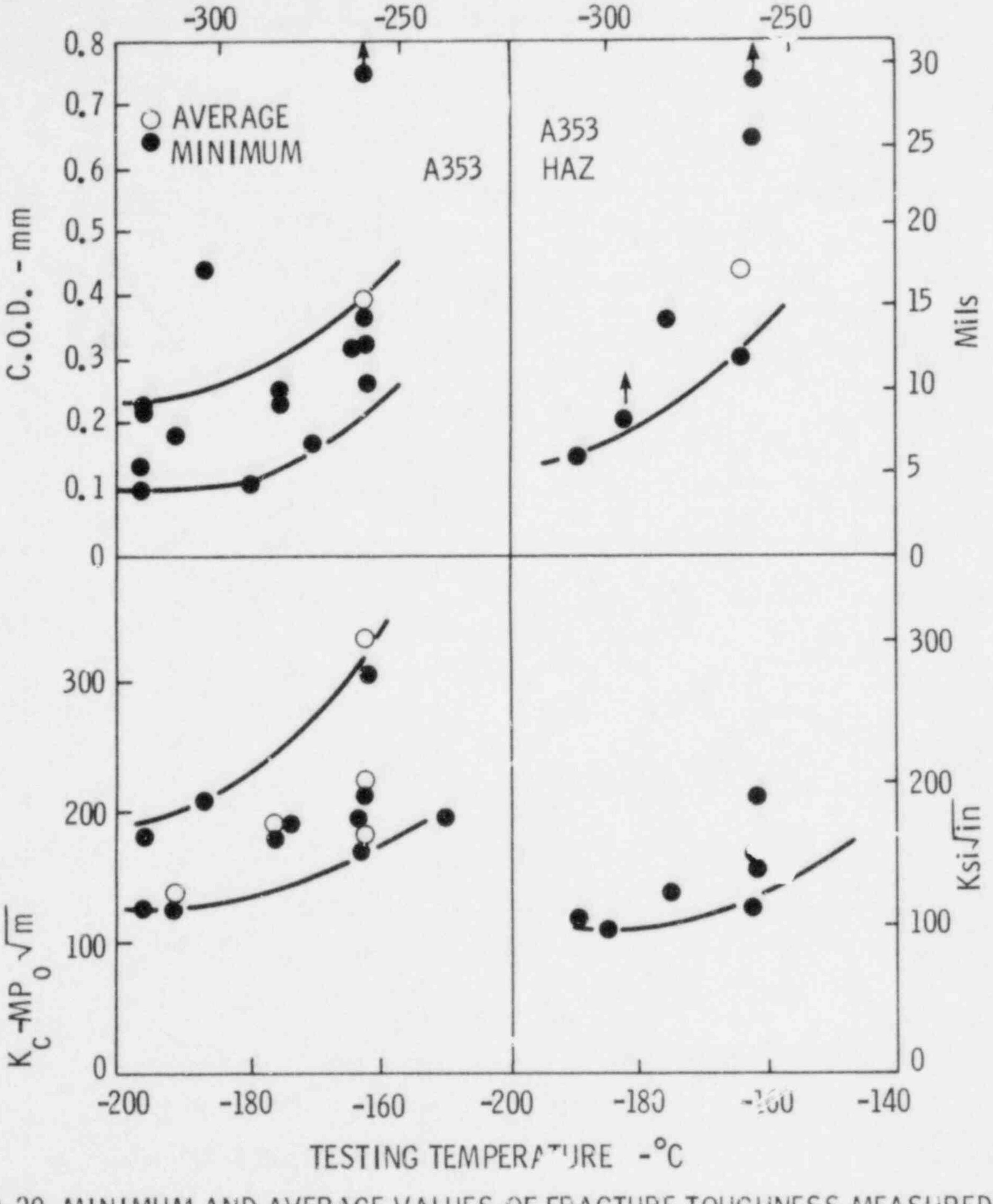


FIG. B.20 MINIMUM AND AVERAGE VALUES OF FRACTURE TOUGHNESS MEASURED BY K_C AND COD FOR A353 STEEL PLATES AND WELD HEAT-AFFECTED ZONES

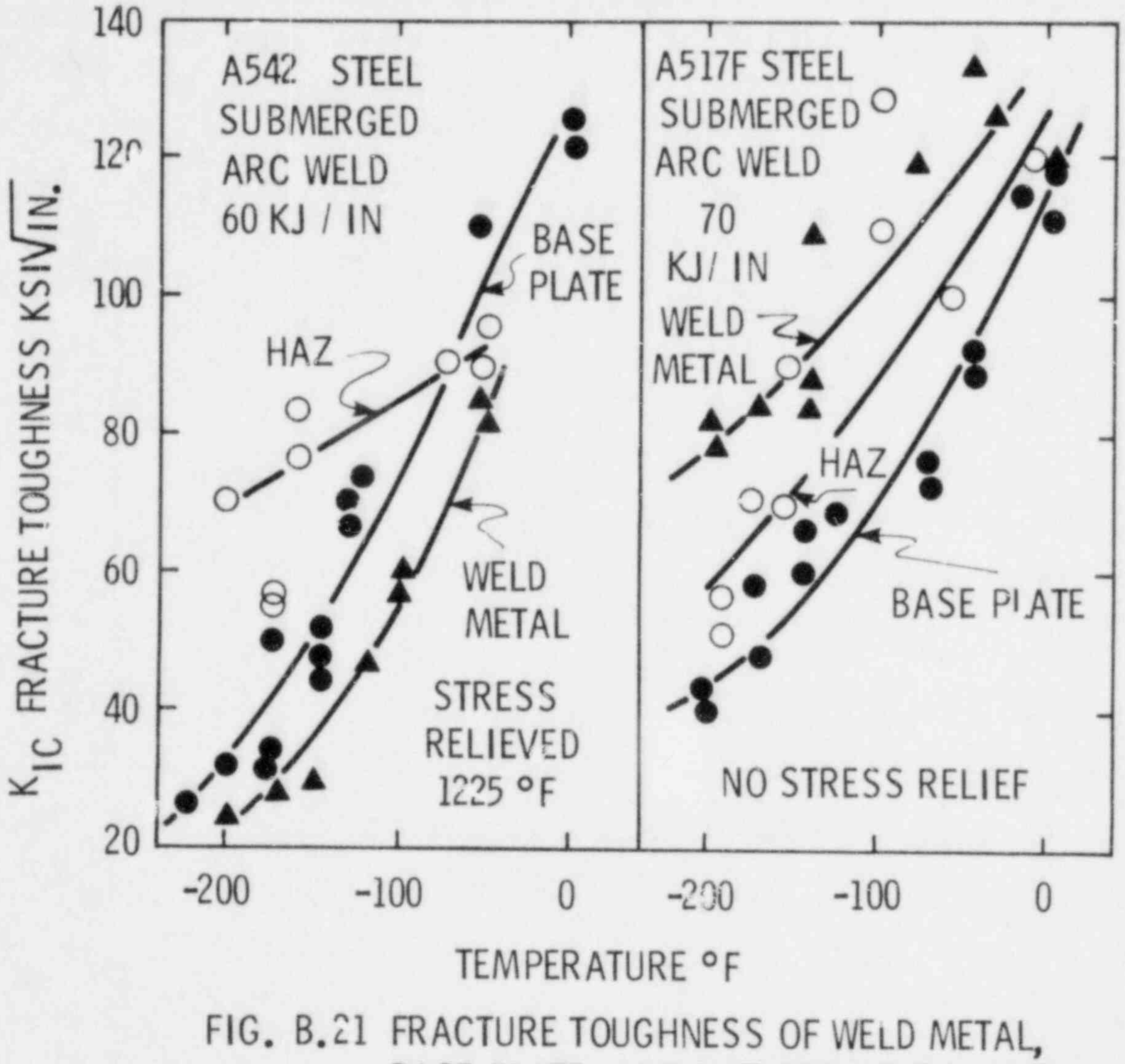


FIG. B.21 FRACTURE TOUGHNESS OF WELD METAL, BASE PLATE, AND HAZ FOR A517 & A542 (A452 HAZ VALUE COMPARABLE TO A387)

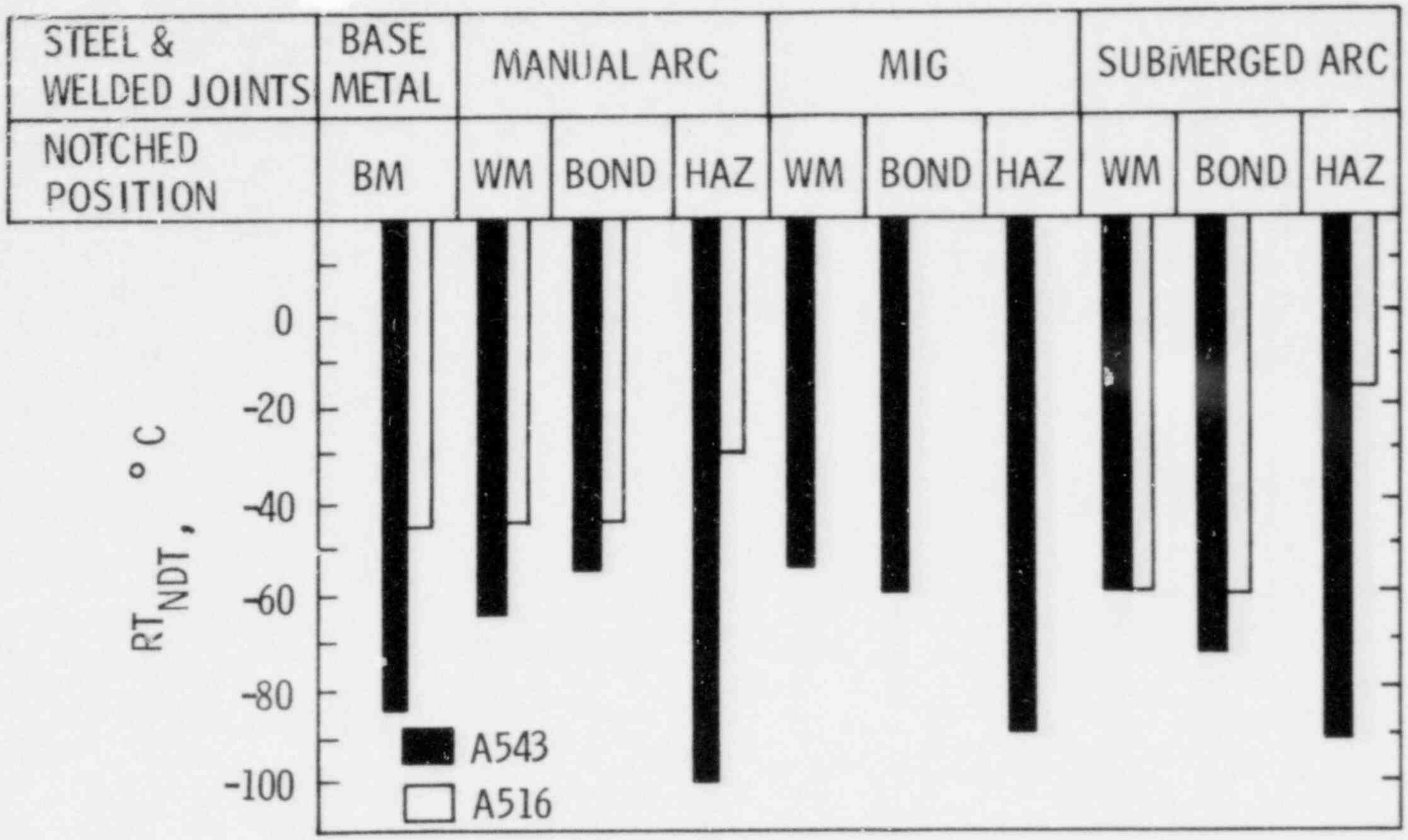


FIG. B.22 COMPARISON OF REFERENCE NIL-DUCTILITY TRANSITION TEMPERATURES, RT_{NDT}

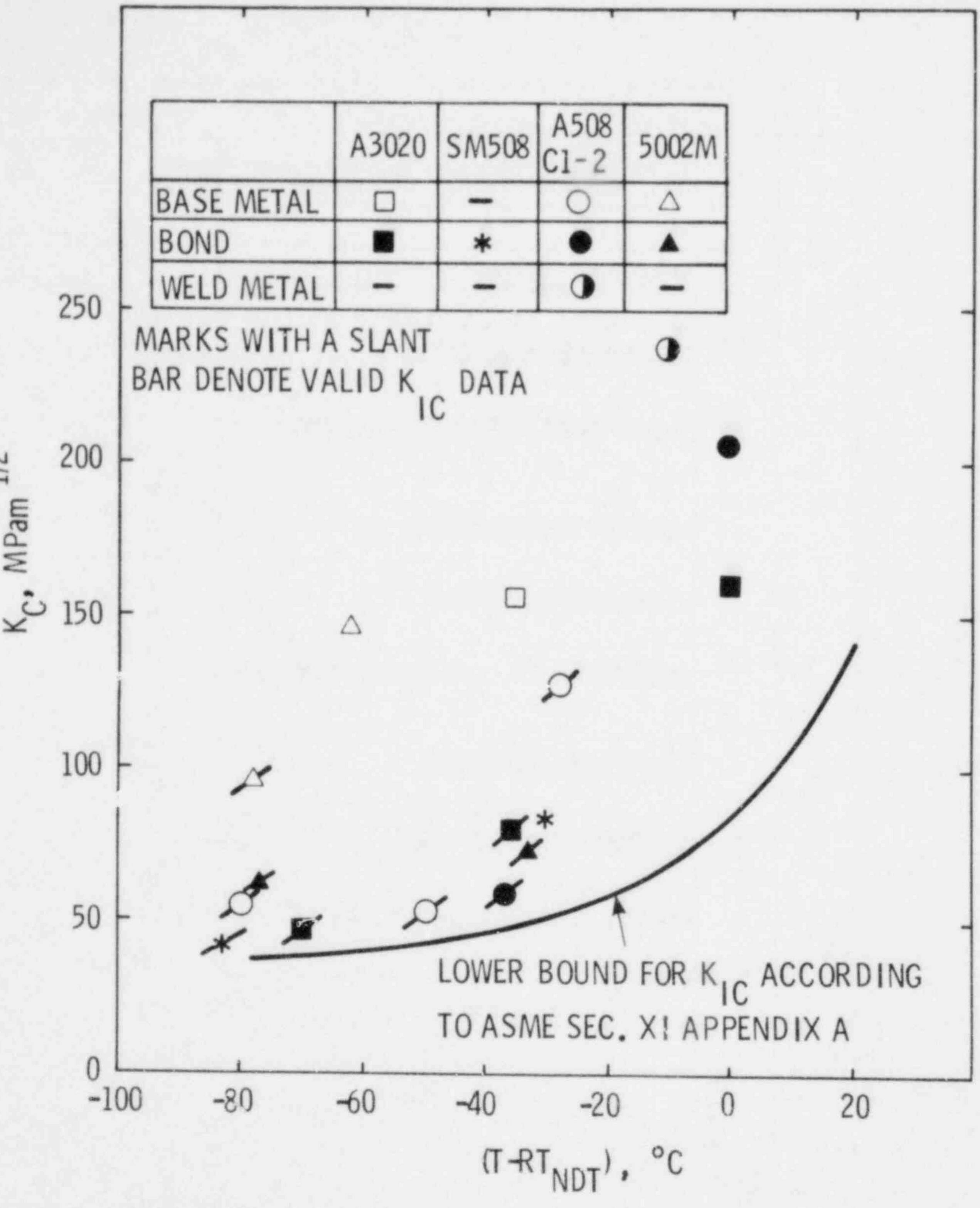


FIG. B.23 K_C DATA OF VARIOUS HEAVY SECTION STEELS FOR PRESSURE VESSEL

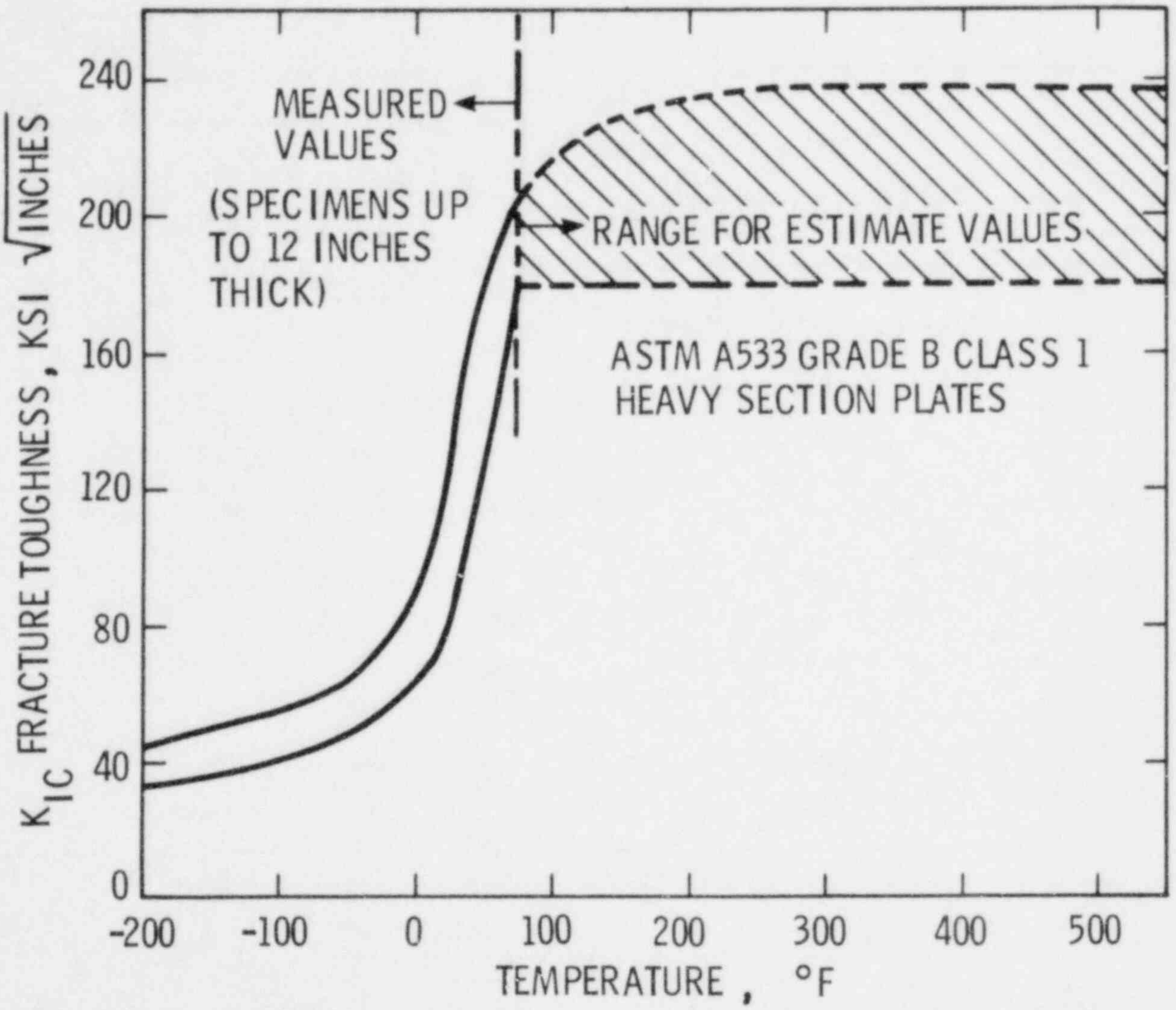


FIG. B. 24 TEMPERATURE DEPENDENCE OF THE STATIC PLANE STRAIN FRACTURE TOUGHNESS OF HEAVY SECTION A533, GRADE B, CLASS 1 PLATES

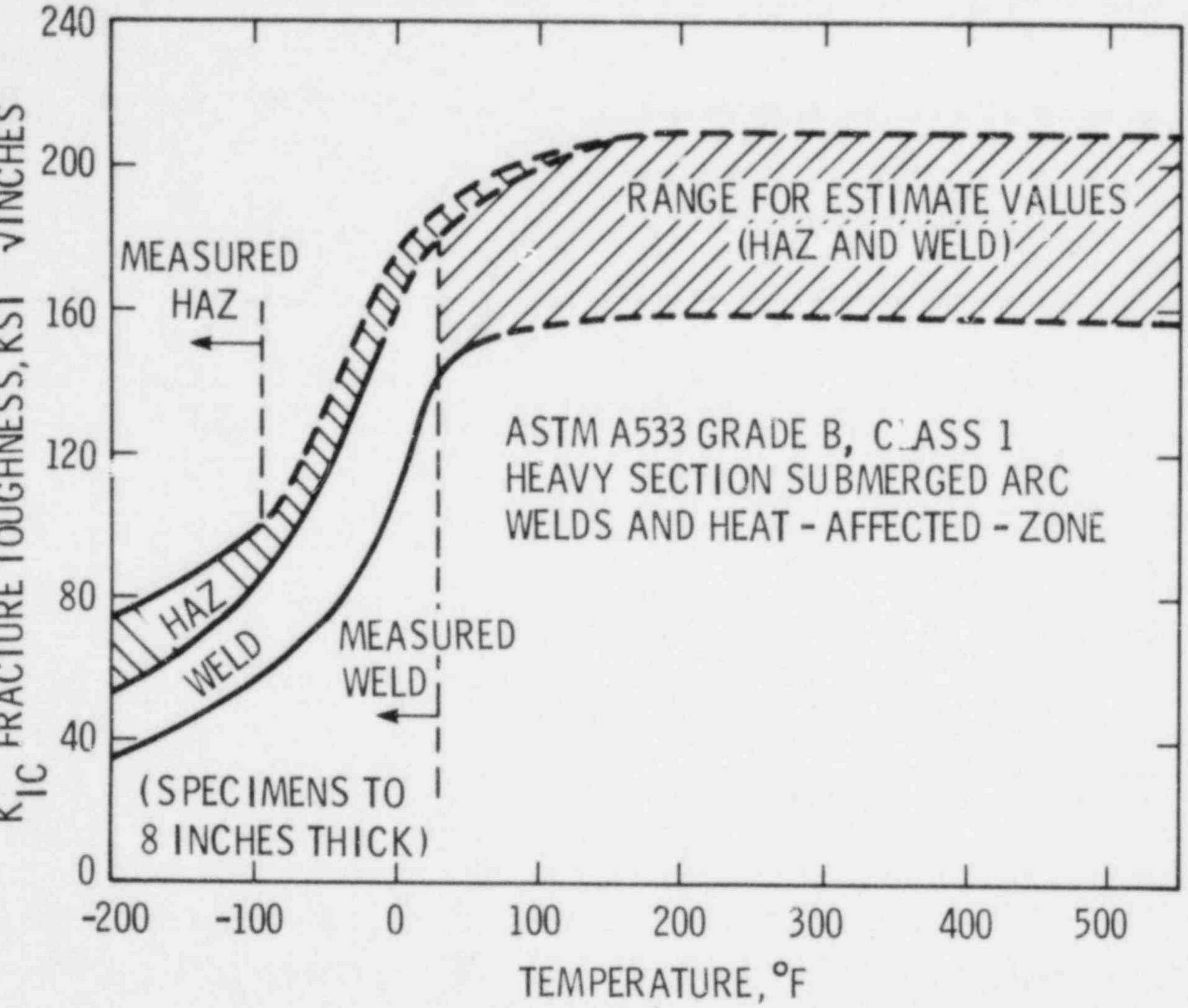


FIG. B-25 TEMPERATURE DEPENDENCE OF THE STATIC, PLANE STRAIN FRACTURE TOUGHNESS OF A533, GRADE B HEAVY SECTION WELDS AND HEAT AFFECTED ZONE

APPENDIX C - DISCUSSION OF GRADES ON WHICH NO INFORMATION IS AVAILABLE

No data were found for grades A-53, A-105 as-forged, A-284, A-618, and A-501. With respect to strength and carbon content, A-501 is virtually identical to A-36. Since carbon and manganese content and grain size mainly control the strength level, and carbon contents are virtually identical, either manganese contents similar to A-36 or grain size control via controlled cooling would be used to determine the strength level with both being beneficial to A-501's toughness. Thus one could expect similar behavior between A-36 and A-501. (A-501 is available in thicknesses up to 1.000 inch only.)

A-53 and A-106 are similar in chemical and mechanical specificatons; the only difference is in deoxidation (semi vs. killed) practice. Thus, one would expect similar impact transition temperature behavior from these two grades, with the A-106 being slightly tougher due to lower dissolved oxygen content. On the other hand, Si promotes more rapid grain growth, and too much Si would thus negate any advantage from the lower oxygen content in A-106. The upper shelf toughness of the killed steel would also be expected to be higher.

For A-283, A-284, and A-285, little or no data were found. They are of similar mechanical specifications (A-283 has no chemical requirements other than P, S, and Cu content, A-284 and A-285 are chemically similar except that A-284 is killed, and A-285 is not). Grouping these similar strength grades and assuming that A-285 is chemically similar, A-283, A-284, and A-285 have a higher allowable C content than the A-53, A-106 type steels. On the basis that higher carbon reduces fracture toughness, one does not expect better toughness for these grades compared to A-53 and A-106.

A-618 is mechanically and chemically identical to A-441, except it is structural tubing. It would be expected to have similar properties.

Compared to A-515 Grades 55 and 60, A-284 Grades C and D allow more carbon at comparable strength levels. Both grades have the same Mn limitation, and A-515 is supposedly "coarse-grained". Apparently the Mn limitation on A-515 is less conservative, that is, it must be approached more closely or average than with the A-284 grades. On this basis, the A-284 steels would rely on a higher C and lower Mn content for a given strength, and would be expected to have a higher NDT than A-515. The two A-284 points found, (one grade B and one grade C) do not suggest that, but these two points do not meet the strength requirements of A-284 either.

A-105 appears to be similar to A-212B, with a slightly more liberal Mn allowance. Then NDT for A-212B should be an upper bound limit for the A-105 NDT. (A-105 is also available in normalized, and quenched and tempered forms for which NDT would be expected to be lower.)

The above material observations have relied heavily upon the limitations set forth in the ASTM standards. It must be recognized that the maximums prescribed in the standards are not exceptionally limiting, and that lower carbon and manganese contents are quite often sufficient to meet physical requirements, especially where more rapid cooling has produced finer microstructures.

APPENDIX D
POSSIBLE METHODS TO EVALUATE LAMELLAR TEARING

In this appendix two systems are described for evaluation of susceptibility to lamellar tearing. The first system is simply a binary system whereby all welded joints are examined and either dismissed or are noted for further study. This system is the one used in this report. The second system is a further look at the joints which were singled out in the first study and assigns a quantitative rating or number for "goodness" to these joints. This second system was not found to be a useful aid for the present study and was thus not used. It is documented here since it may prove useful in the future. In order to make the description complete, the system is illustrated on a particular structure.

D.1 Qualitative Selection of Susceptible Joints

Configurations which are particularly susceptible are shown in Fig. D1. The configuration A is by far the most common of these. The worst variation of this is the full penetration weld of a cruciform joint. A simple symmetric fillet weld is somewhat better on T-joints. The large single sided groove weld of a corner joint seen in Fig. D1B is a bad configuration, but since the lamellar tearing would almost always extend to the free edge this joint is not likely to cause trouble since defects would be easily found during fabrication. Configuration C is a special case of configuration A, as is configuration D when the pipe is simply butted against the plate and welded all around. Another common variation of configuration A is the I-beam to I-beam joint. Configuration D has another variation which eliminates lamellar tearing danger in the plate. This is accomplished by cutting a hole in the plate through which the pipe extends and is then welded all around. Unfortunately this design may result in lamellar tearing in the pipe wall.

In Fig. D2 are shown several configurations which are good from the standpoint of lamellar tearing. The first is a butt weld in the rolling direction. Included here are I-beam and plate splices. The flange-to-flange joint in Fig. D2B is also a favorable orientation. The T-joint of configuration C is a bad orientation but the thin horizontal member is flexible enough to accommodate the thermal strains from the welding process. Configuration D is not a favorable configuration but if only compressive loads are allowed on the vertical member then the joint is acceptable. Configuration E is a member which has lamellar tearing present (perhaps from a lug which had been removed after construction) but is only loaded in tension or compression parallel to the tears. This member would be of little concern.

In section 5.4 a set of factors which affect susceptibility to lamellar tearing were listed, explained, and referenced. These factors are utilized here in an attempt to rank the joints in a structure with regard to their susceptibility to lamellar tearing.

In an effort to be thorough, i.e., to consider all factors, and also be objective, at least relative to each joint, all of the factors have been assigned numerical points or point ranges. Some factors are only bad (-), some only good (+), and some could be either good or bad. The factors are given in Table D.1 and the points assigned are explained below. The letters at the left

Table D.1
Points Assigned to Various Factors on
a Weld Selected for Further Study

	Factor	Points Assigned
A	Sulfur Content	-2 to +2
B	Plate Thickness	0 to +7
C	Weld Bead Volume	0 + 2
D1	Low Hydrogen Electrode	-2,0
D2	Electrode/Parent Matl. Yield	0 to +5
E1	Rolling Dir/HAZ Orientation	0 to +10
E2	Service Load (tension,shear)	0,5
E3	Full Penetration/Balance	-2 to +2
F	ST Reduction of Area	0 to +7
G1	Buttering	0,+2
G2	Peening	0,+2
G3	High Heat Input	0,+1
H1	Pre-heating	0
H2	Restraint	-5,0
I	Post Welding Ultrasonic Test	0 to +5

of the factors refer to the paragraph headings in section 5.4 where the factors are discussed. The numerical values selected for each factor could be the subject of an interesting debate between "experts" in the field. The values chosen here merely illustrate the system.

The nominal T-joint is used as a basis for the system and other joints are compared to it. The joint would be made of ordinary structural steel (A=0) and would be made of thick plate (B=0) so tht the weld bead volume would be greater than 0.1 sq in (C=0). An E-7018 low hydrogen electrode (D1=0) would be used so that the ratio of yield stress of the electrode to that of the parent metal would be about 1.5 (D2=0). The base plate in the T-joint would have its rolling direction parallel to the HAZ boundary (E1=0), the service load would put this short thickness direction in tension (E2=0) and the weld would be a balanced full penetration weld (E3=0). There would have been no short transverse reduction of area measurements made (F=0). The weld area would not have been buttered, with no peening between passes and medium heat input used (G1=G2=G3=0). Pre-heating may or may not have been used (H1=0) but no restraint would have been caused by this or other fabrication procedures. No post welding ultrasonic tests would have been made (I=0). This nominal joint deserves concern but cannot be rated either definitely good or definitely bad without further information. The joint which rates greater than zero or less than zero is simply better or worse than the nominal joint.

This sytem is now illustrated with the example of the steam generator and reactor coolant pump supports in the Calvert Cliffs facility.

The upper support key bracket on the steam generator (two brackets per generator) is an all welded unit which has four locations of concern as identified in Fig. E1. The reactor coolant pump has several joints which are examined also. Figures E2 through E4 show these joints. The point system is applied to each joint with the results listed in Table D2.

Table D.2
Lamellar Tearing Factors Applied to Calvert Cliffs

Joint Number	1	2	3	4	5	6	7
Sulfur Content	0	0	0	0	(	0	0
Plate Thickness	0	0	0	0	0	0	0
Weld Bead Volume	0	0	0	0	0	0	0
Low Hydrogen Electrode	0	0	0	0	0	0	0
Electrode/Parent Matl. Yield	2	2	2	2	2	2	2
Rolling Dir/HAZ Orientation	0	0	0	0	0	0	0
Service Load (tension,shear)	5	5	5	0	0	0	0
Full Penetration/Balance	2	-1	-2	-1	2	-2	-1
ST Reduction of Area	0	0	0	0	0	0	0
Buttering	0	0	0	0	0	0	0
Peening	0	0	0	0	0	0	0
High Heat Input	0	0	0	0	0	0	0
Pre-heating	0	0	0	0	0	0	0
Restraint	0	-5	-1	0	0	3	0
Total	9	1	4	1	4	3	1

Note: σ_{E7018} = 57 ksi σ_{parent} = 50 ksi

Note the range in total points varies from one point, slightly better than the nominal joint, to nine points, which can be considered no problem. All joints are better than the nominal zero but all but one would require remedial action or an even more detailed study where other factors such as actual stresses would be considered.

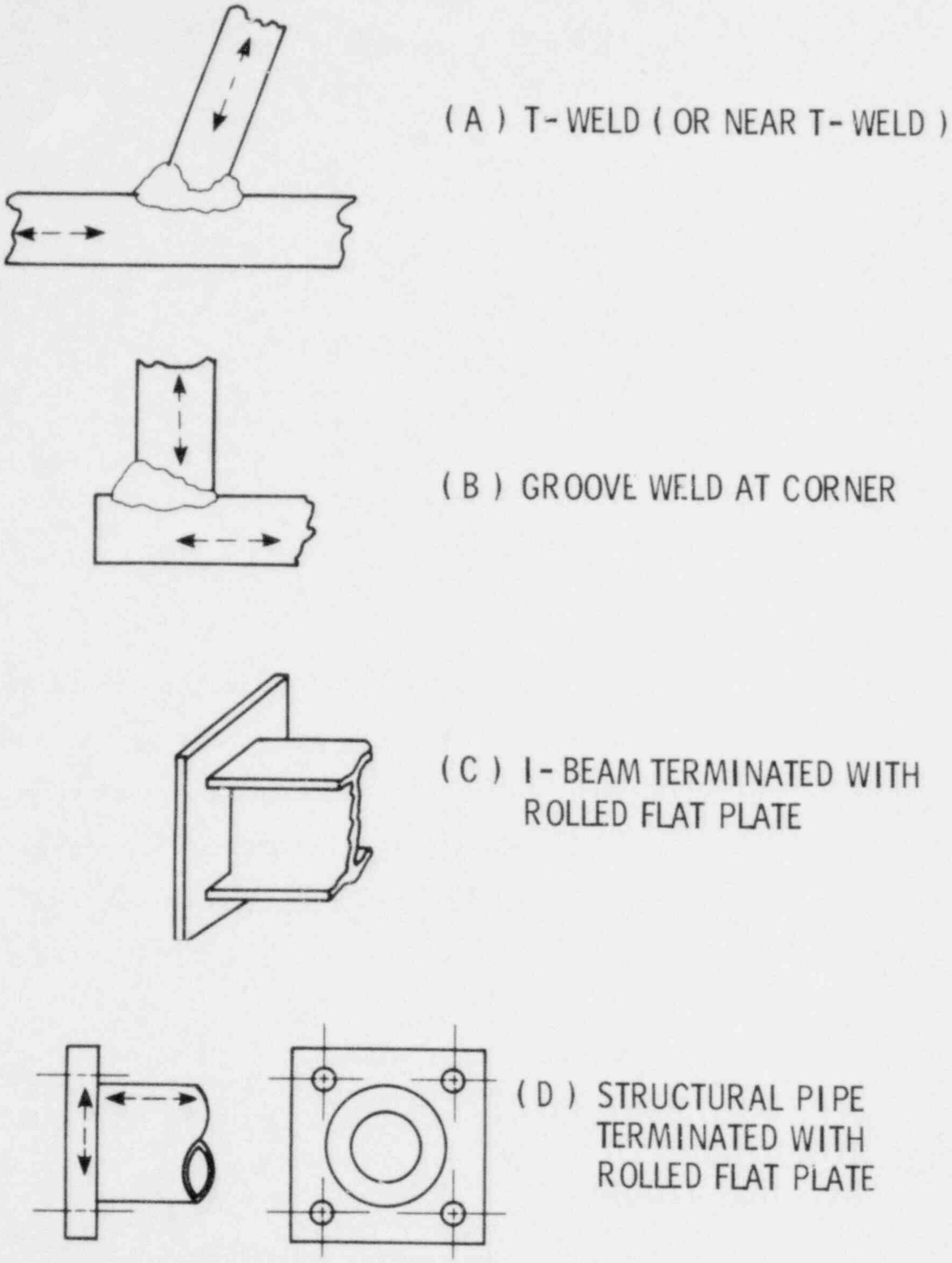
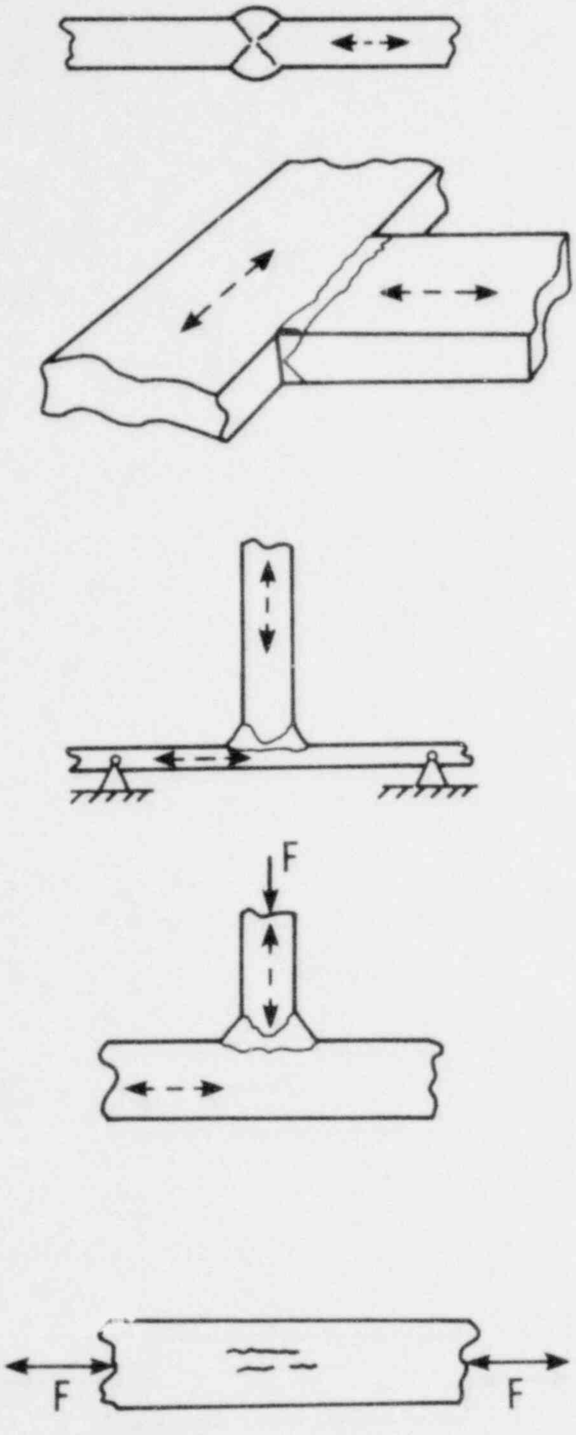


FIGURE D1 JOINT GEOMETRIES WHICH ARE PARTICULARLY SUSCEPTIBLE TO LAMELLAR TEARING. DASHED LINE INDICATES ROLLING DIRECTION.



(A) BUTT WELD IN ROLLING DIRECTION

(B) FLANGE-TO-FLANGE WELD

(C) T-WELD ONTO THIN SECTION WITH REMOTE SUPPORT

(D) T-WELD WITH ONLY COMPRESSION ON THE VERTICAL LEG

(E) LAMELLAR TEARING PRESENT BUT MEMBER LOADED IN TENSION-COMPRESSION ONLY

FIGURE D2. SEVERAL JOINT CONFIGURATIONS WHICH ARE RESISTANT TO LAMELLAR TEARING OR WILL CARRY DESIGN LOADS DESPITE LAMELLAR TEARING.

APPENDIX E

COMPONENT SUPPORT STRUCTURAL DETAILS

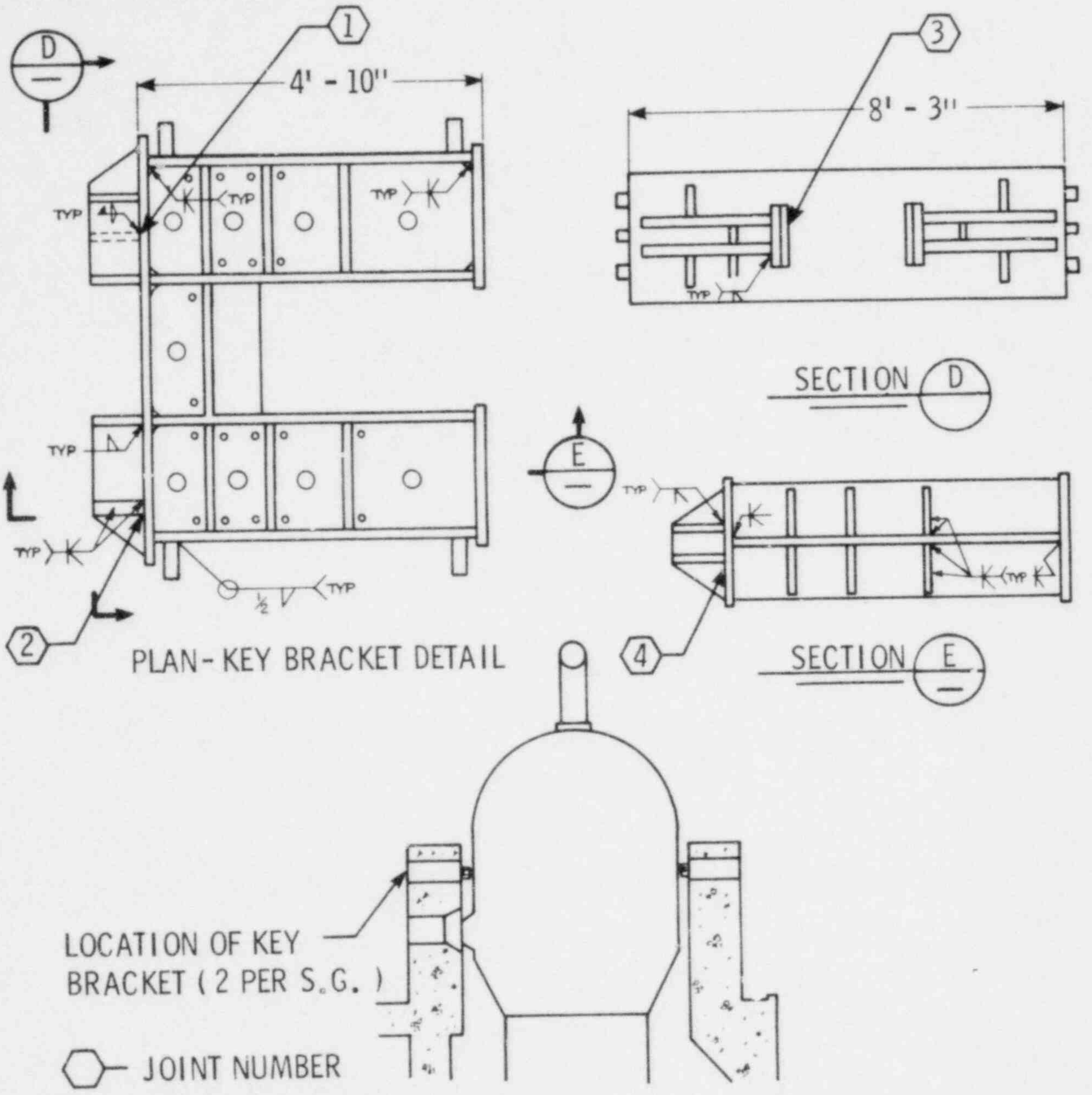


FIG. E1. STEAM GENERATOR DETAIL FROM CALVERT CLIFFS (BECHTEL DWG 6750- C - 267)

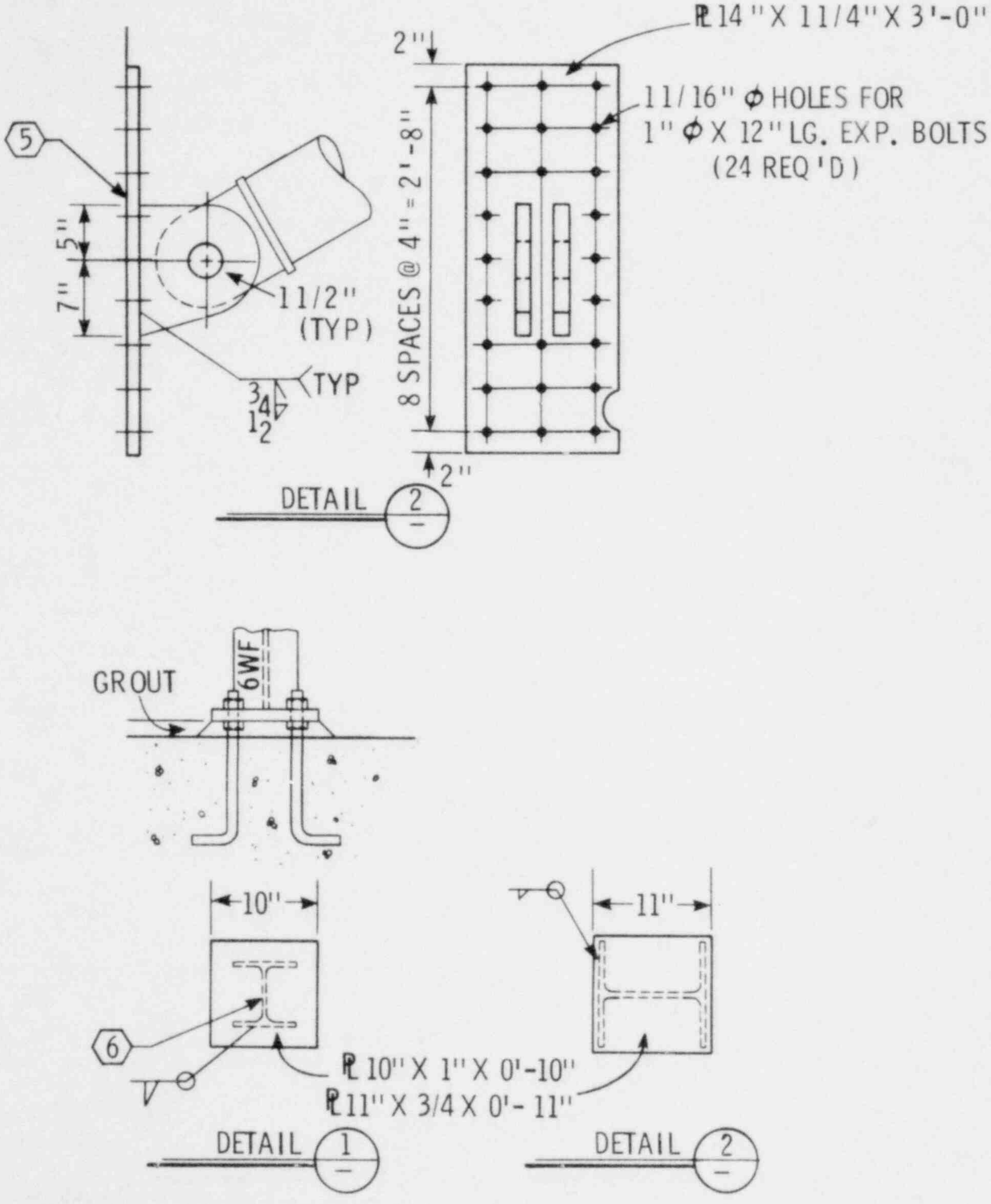


FIG. E2. JOINTS 5 (BECHTEL DWG 6750-C-367) AND 6 (BECHTEL DWG 6750-C-278) FROM CALVERT CLIFFS RC PUMP SUPPORT

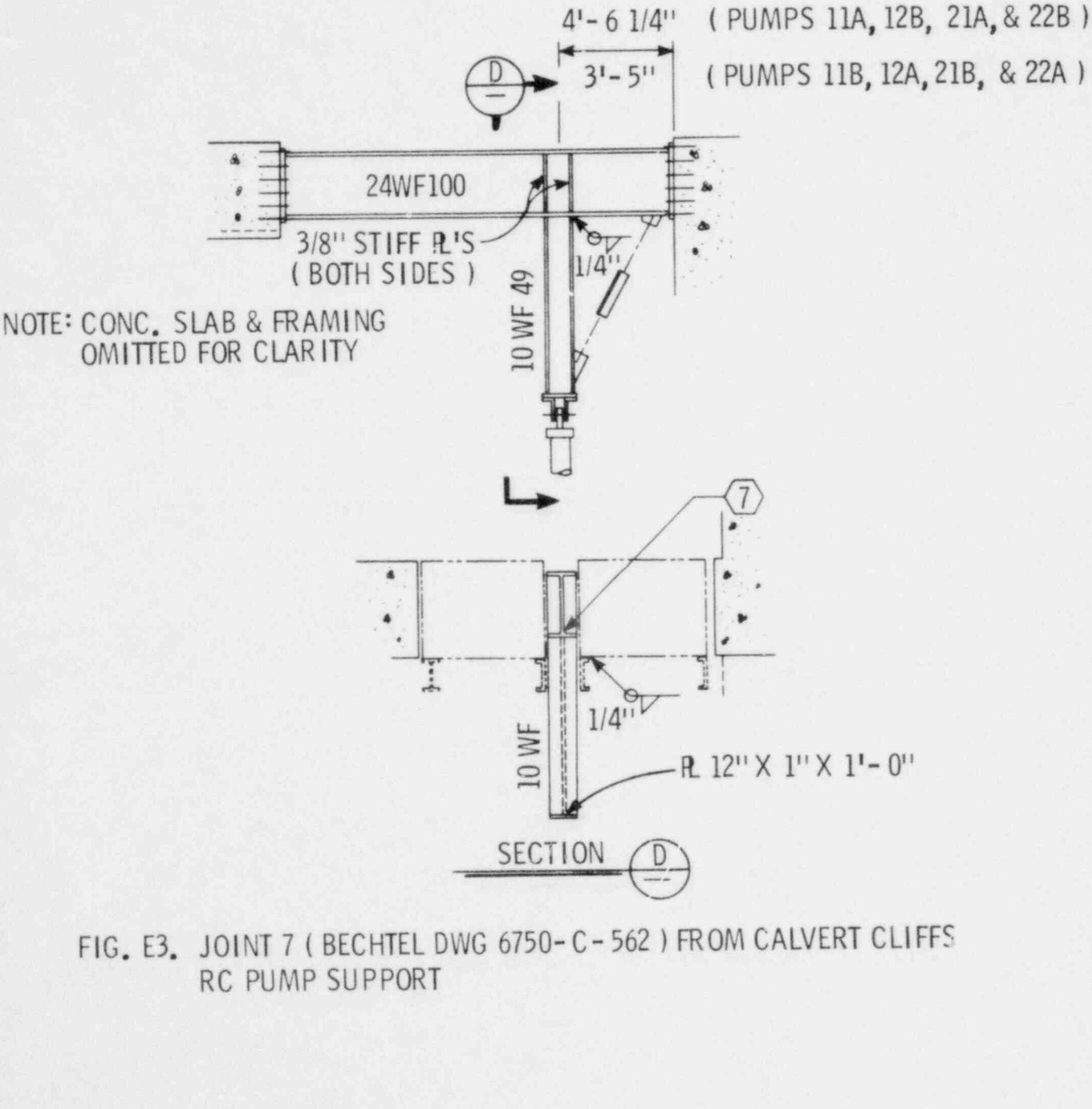


FIG. E3. JOINT 7 (BECHTEL DWG 6750-C-562) FROM CALVERT CLIFFS RC PUMP SUPPORT

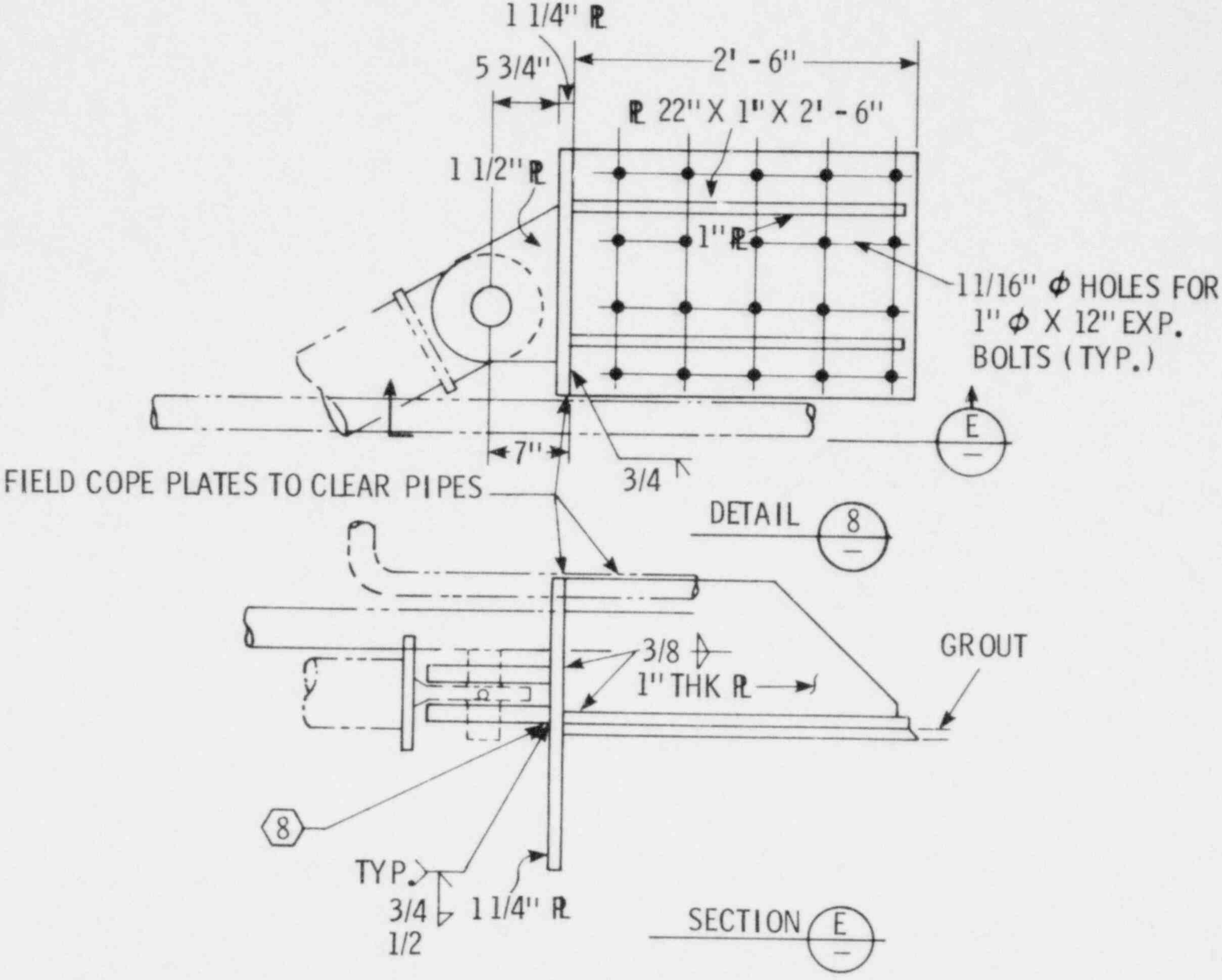


FIG. E4. JOINT 8 (BECHTEL DWG 6750-C-562) FROM CALVERT CLIFFS RC PUMP SUPPORT

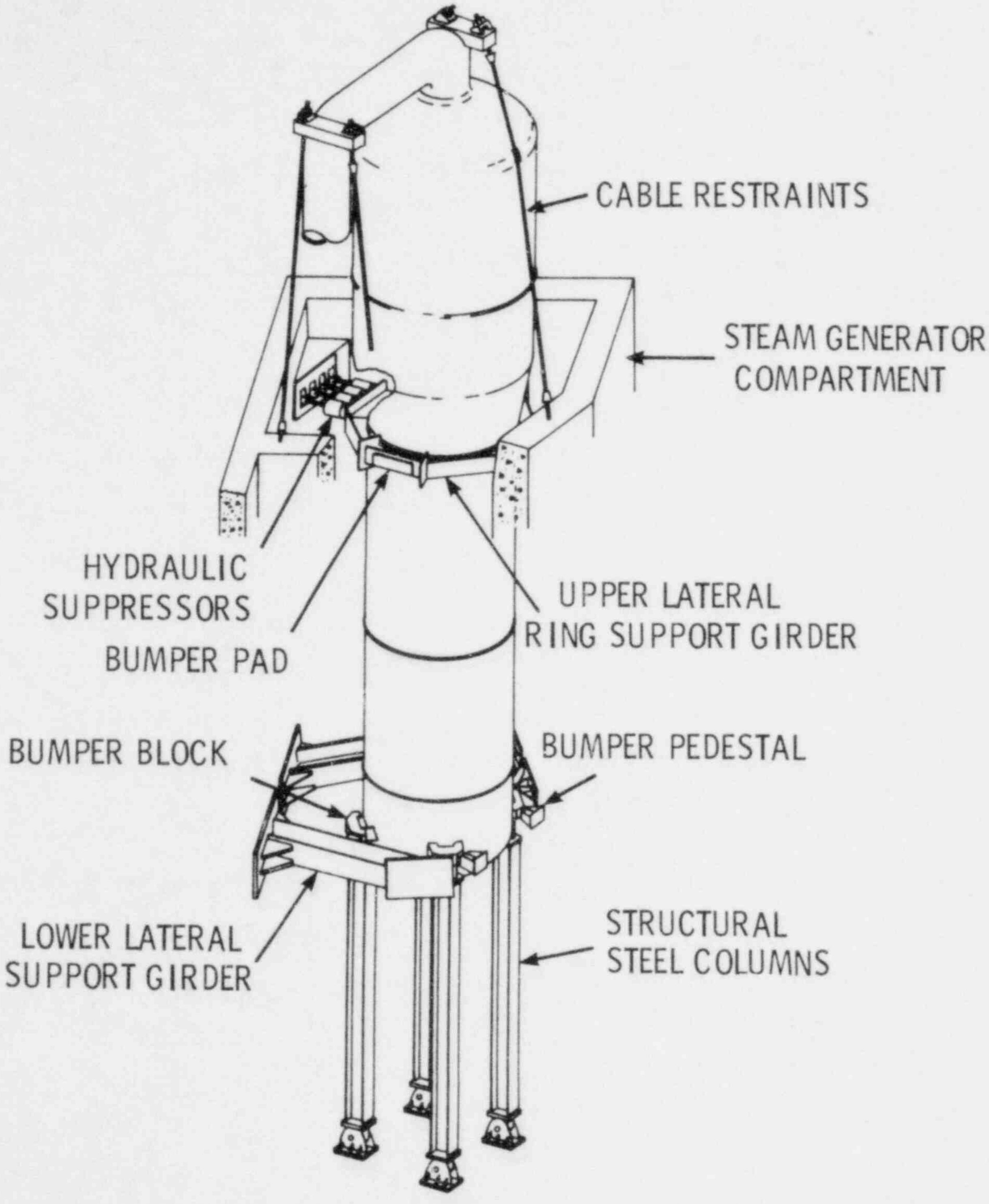


FIG. E5. STEAM GENERATOR SUPPORT STRUCTURE FOR PRAIRIE ISLAND.

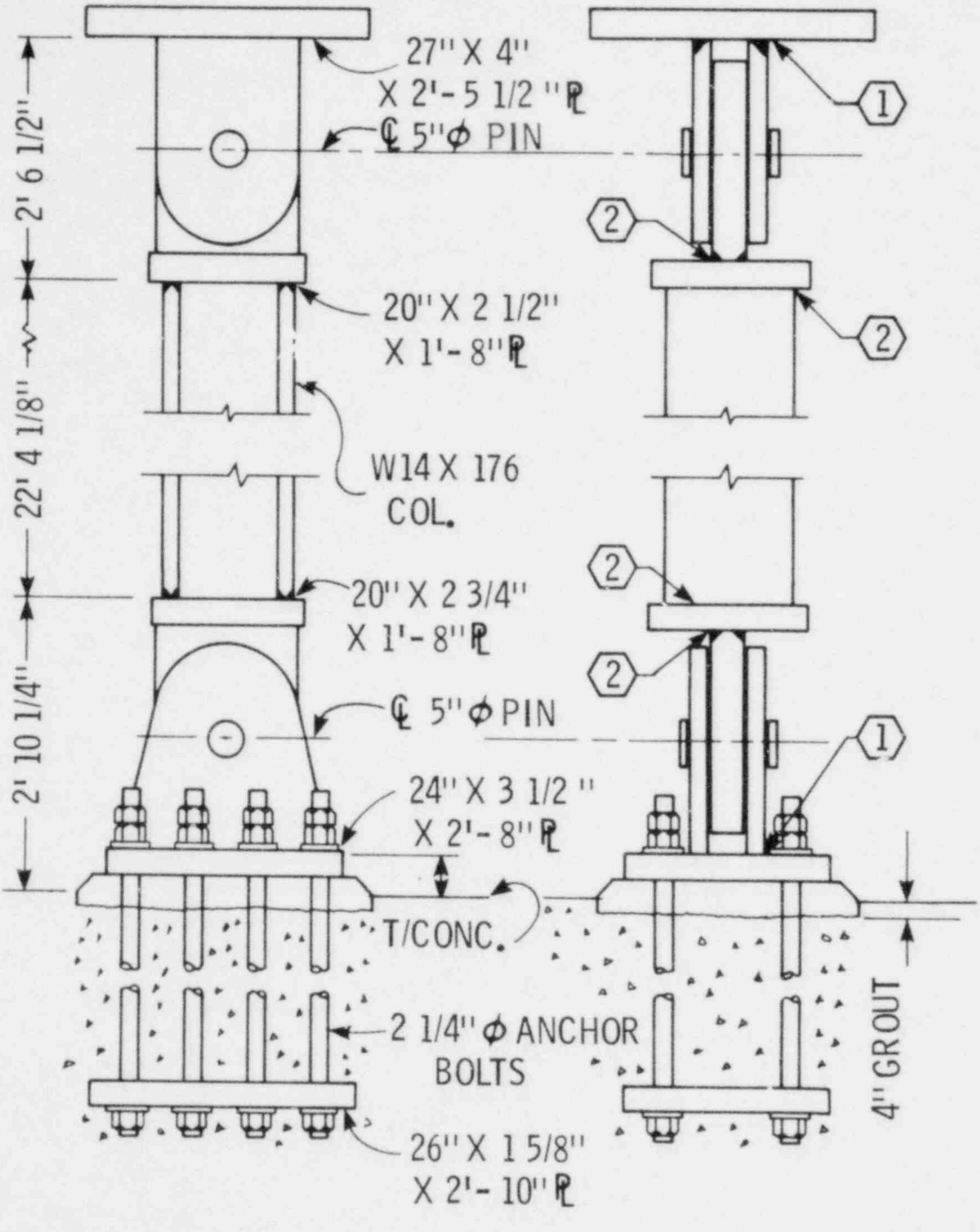


FIG. E6. COLUMN ENDS OF THE PRAIRIE ISLAND STEAM GENERATOR SUPPORT STRUCTURE.

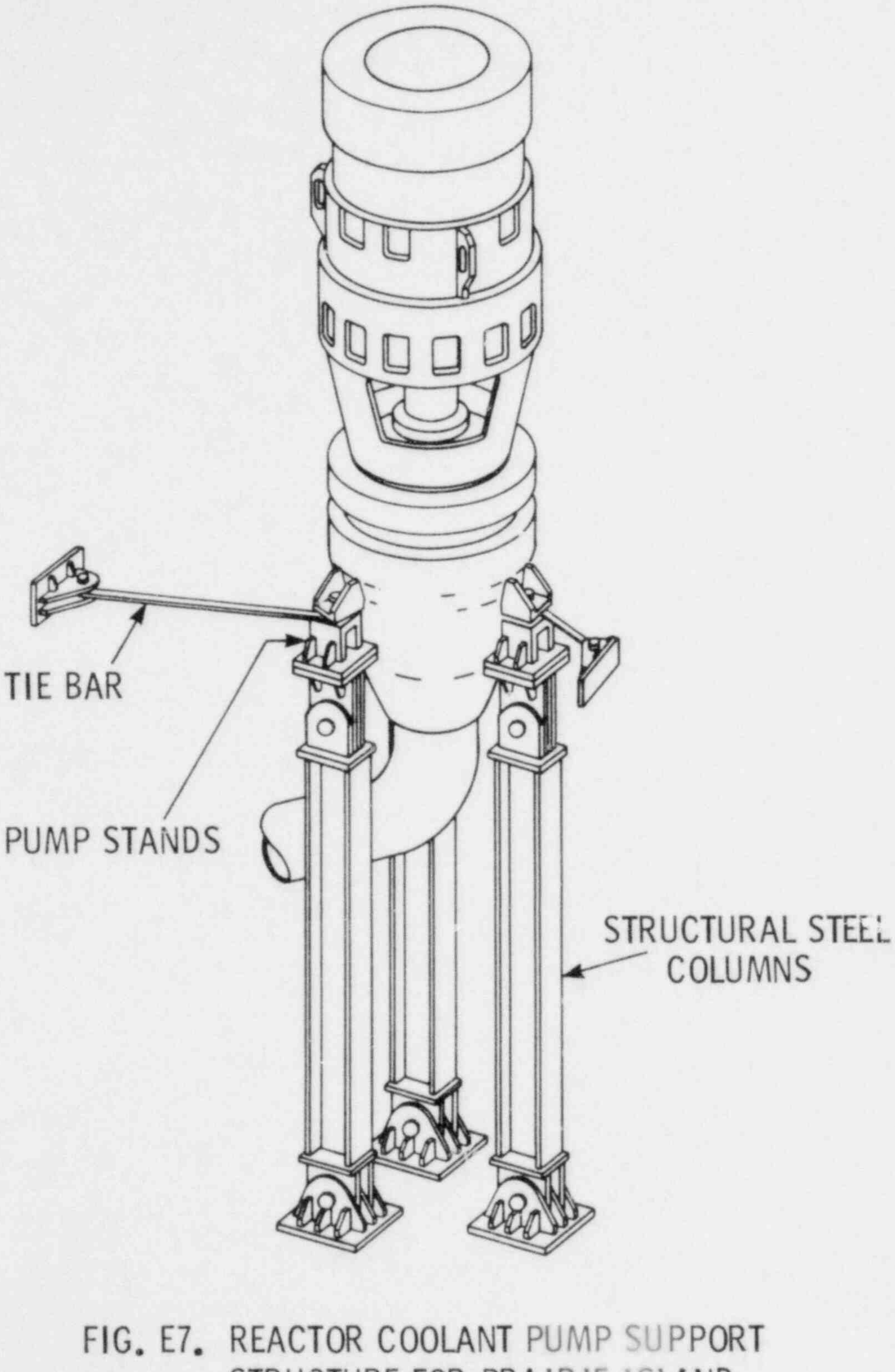


FIG. E7. REACTOR COOLANT PUMP SUPPORT STRUCTURE FOR PRAIRIE ISLAND.

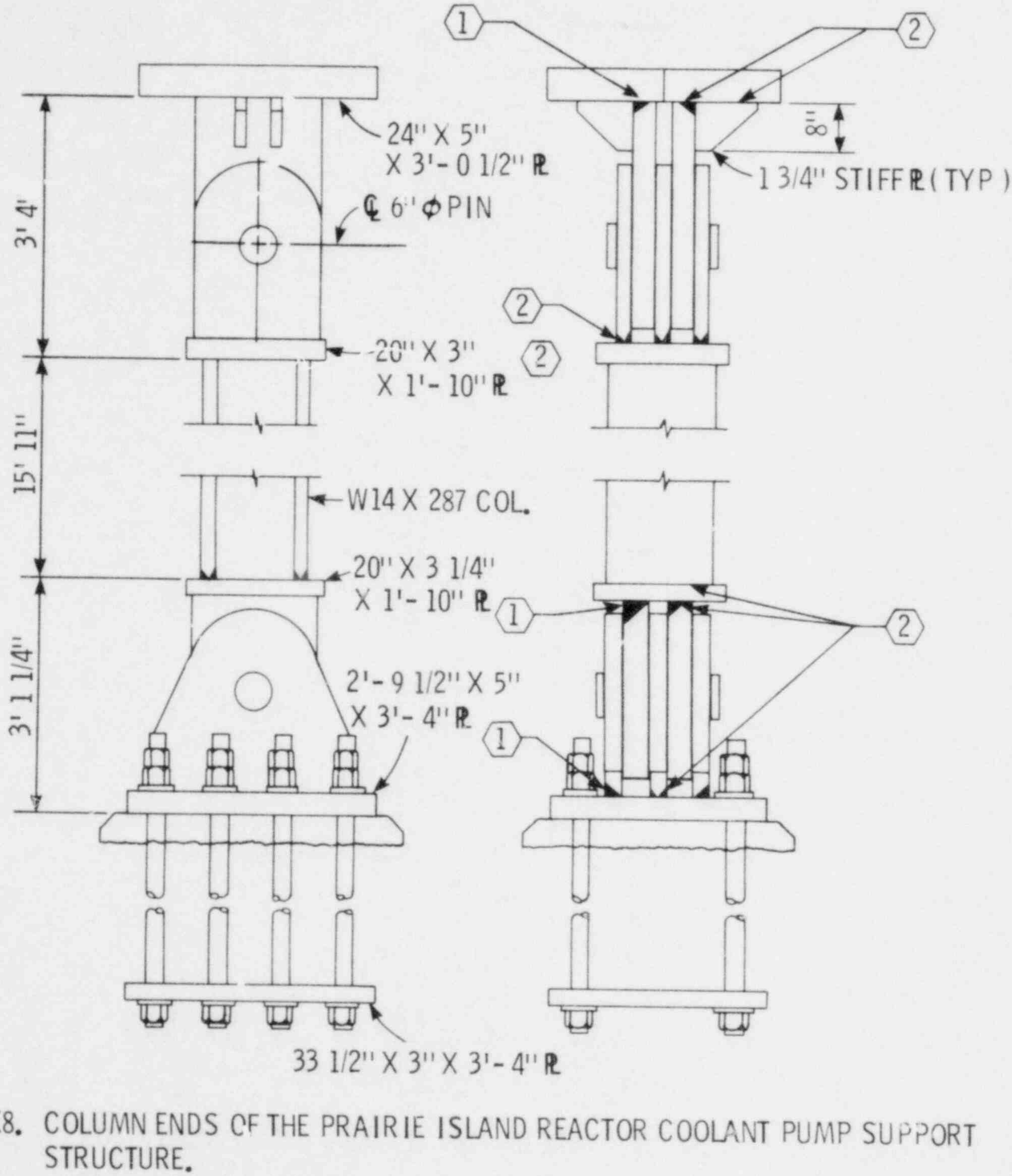


FIG. E8. COLUMN ENDS OF THE PRAIRIE ISLAND REACTOR COOLANT PUMP SUPPORT STRUCTURE.

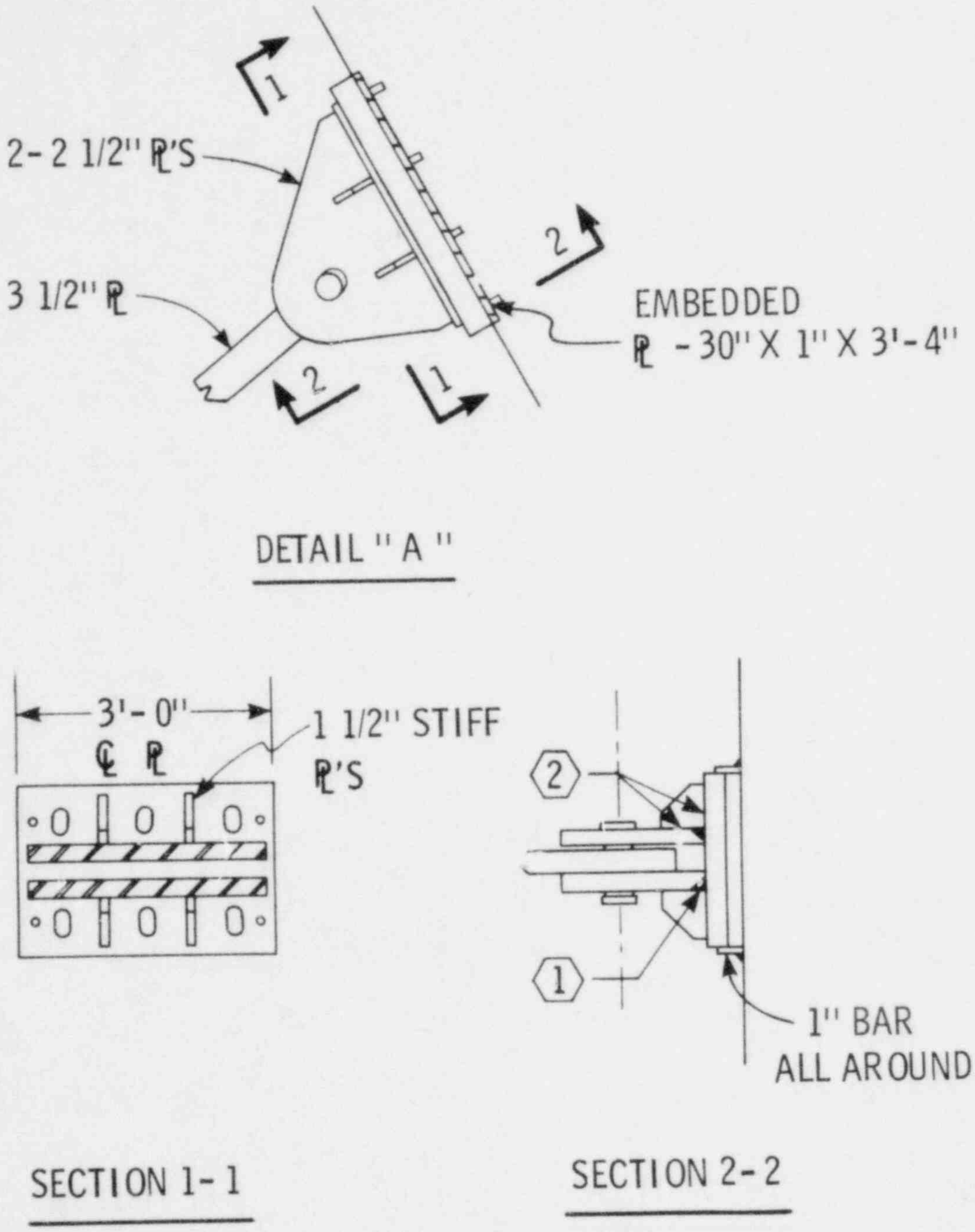


FIG. E9. TIE BAR ASSEMBLY FOR THE PRAIRIE ISLAND REACTOR COOLANT PUMP SUPPORT STRUCTURE.

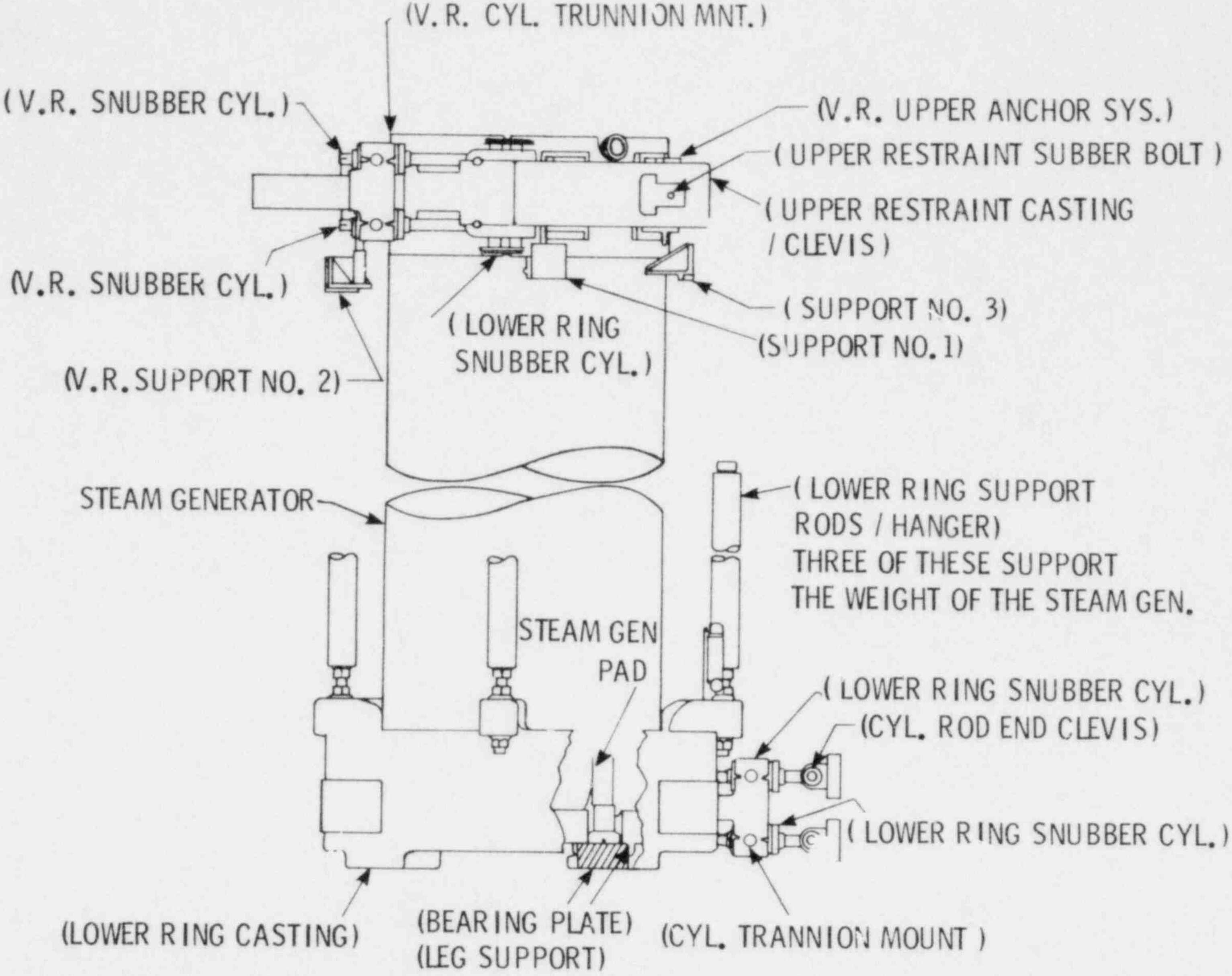
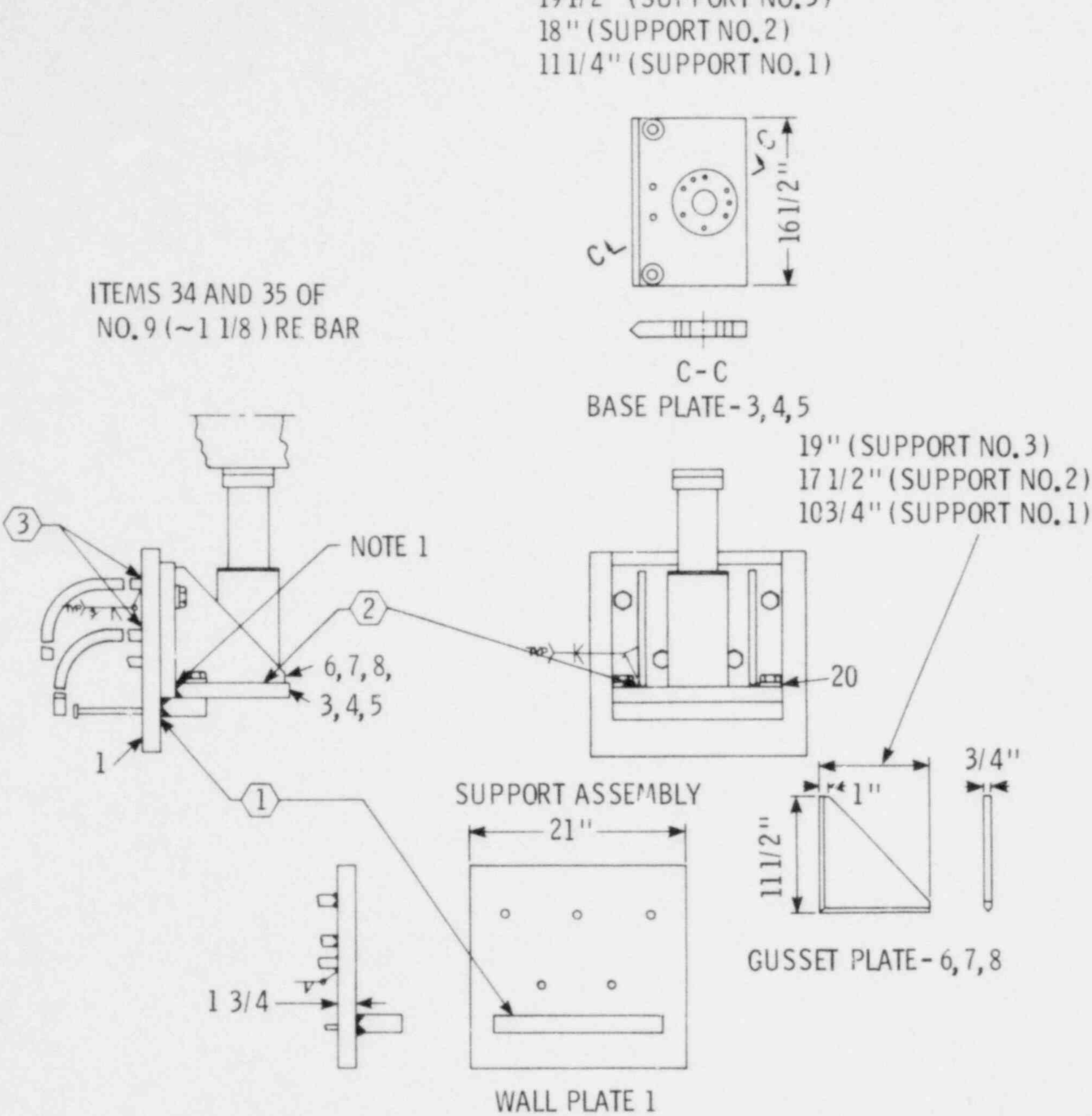


FIG. E10. STEAM GENERATOR SUPPORT STRUCTURE FOR THE SURRY 1 AND 2 PLANT.



Note 1: This joint is dismissed since it extends to the free edge of the vertical member making Lamellar tearing visible.

FIG. E11. UPPER RESTRAINT SUPPORT ASSEMBLY WHICH SUPPORTS THE UPPER RING RESTRAINT CASTING AROUND THE STEAM GENERATOR OF SURRY 1 AND 2. (TAKEN FROM DWG 11448-FM-51K)

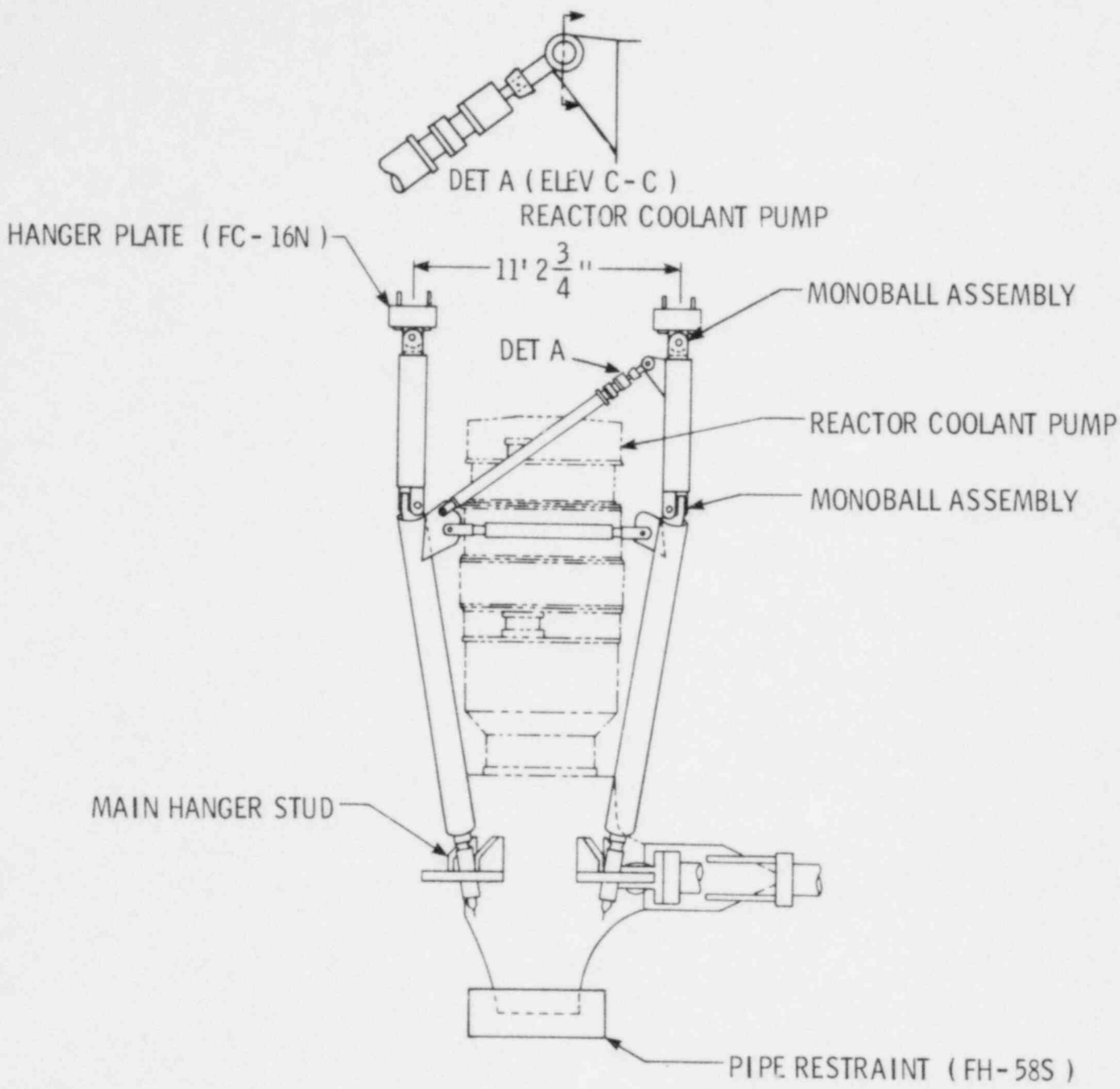


FIG. E12. REACTOR COOLANT PUMP SUPPORT STRUCTURE FOR THE SURRY 1 AND 2 PLANTS.

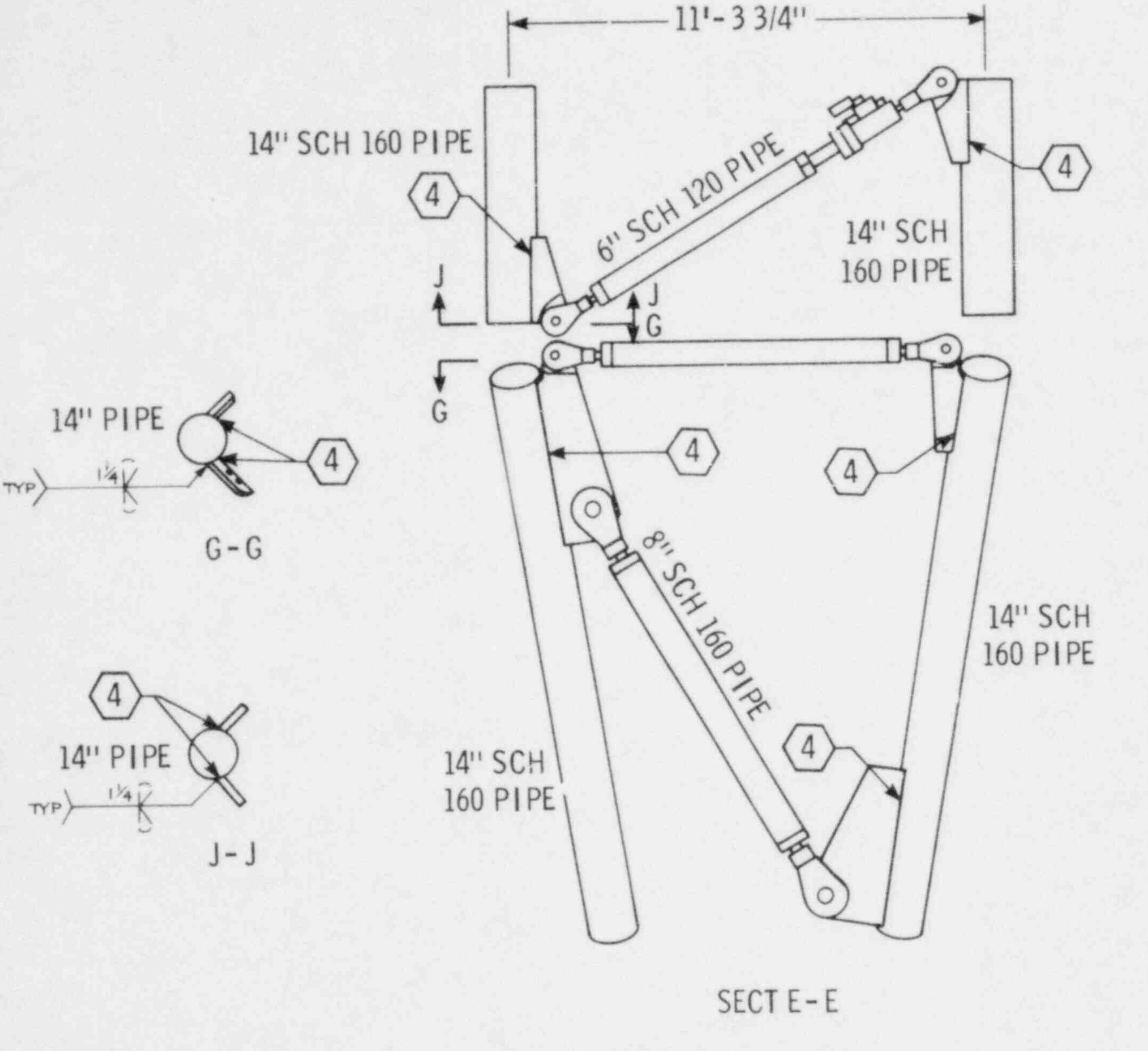


FIG. E13. CLEVIS ATTACHMENT POINTS ON THE REACTOR COOLANT PUMP SUPPORT FOR THE SURRY 1 AND 2 PLANTS.

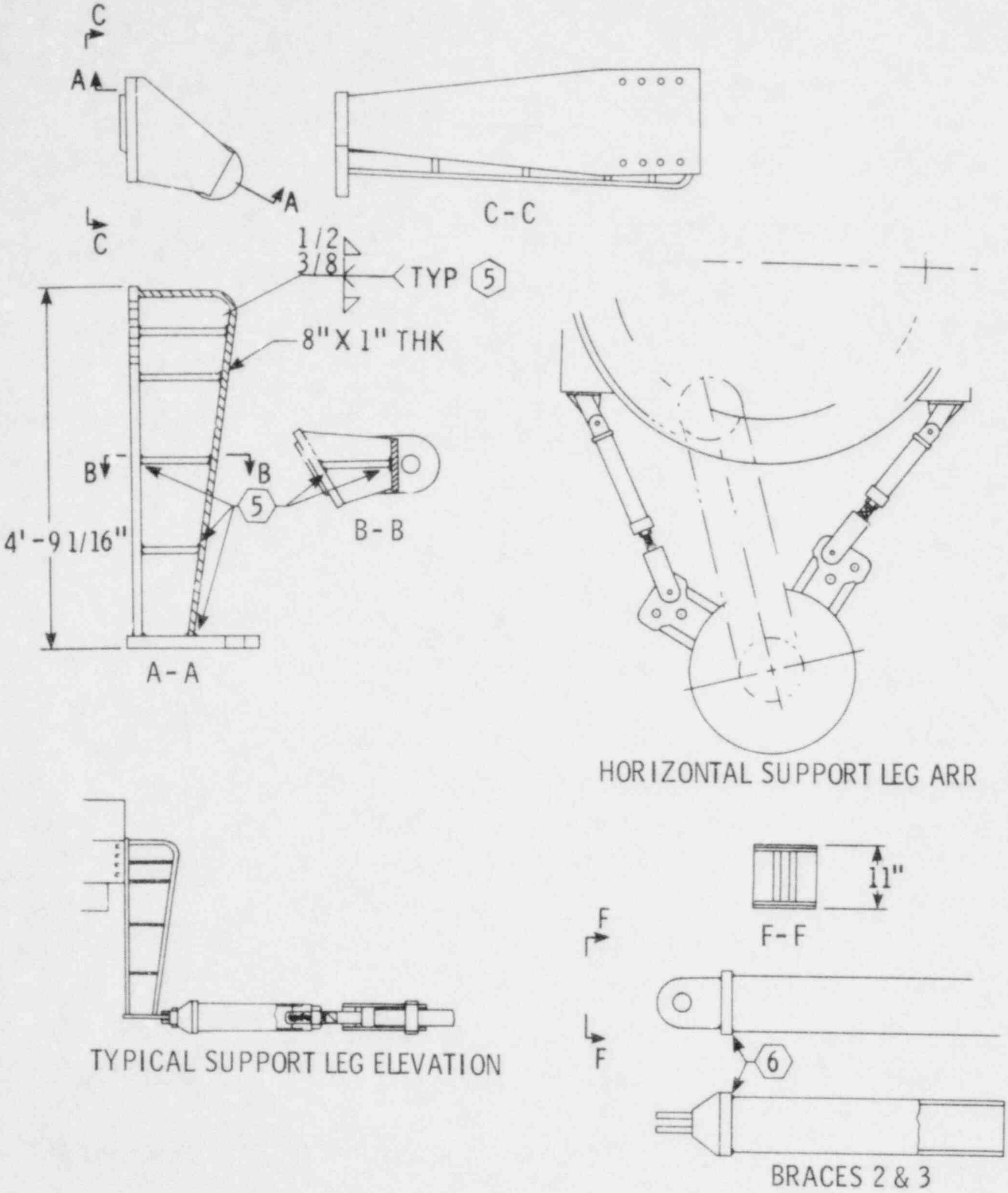


FIG. E14. HORIZONTAL SUPPORT LEG ATTACHMENT ON REACTOR COOLANT PUMP FOR SURRY 1 AND 2 PLANTS

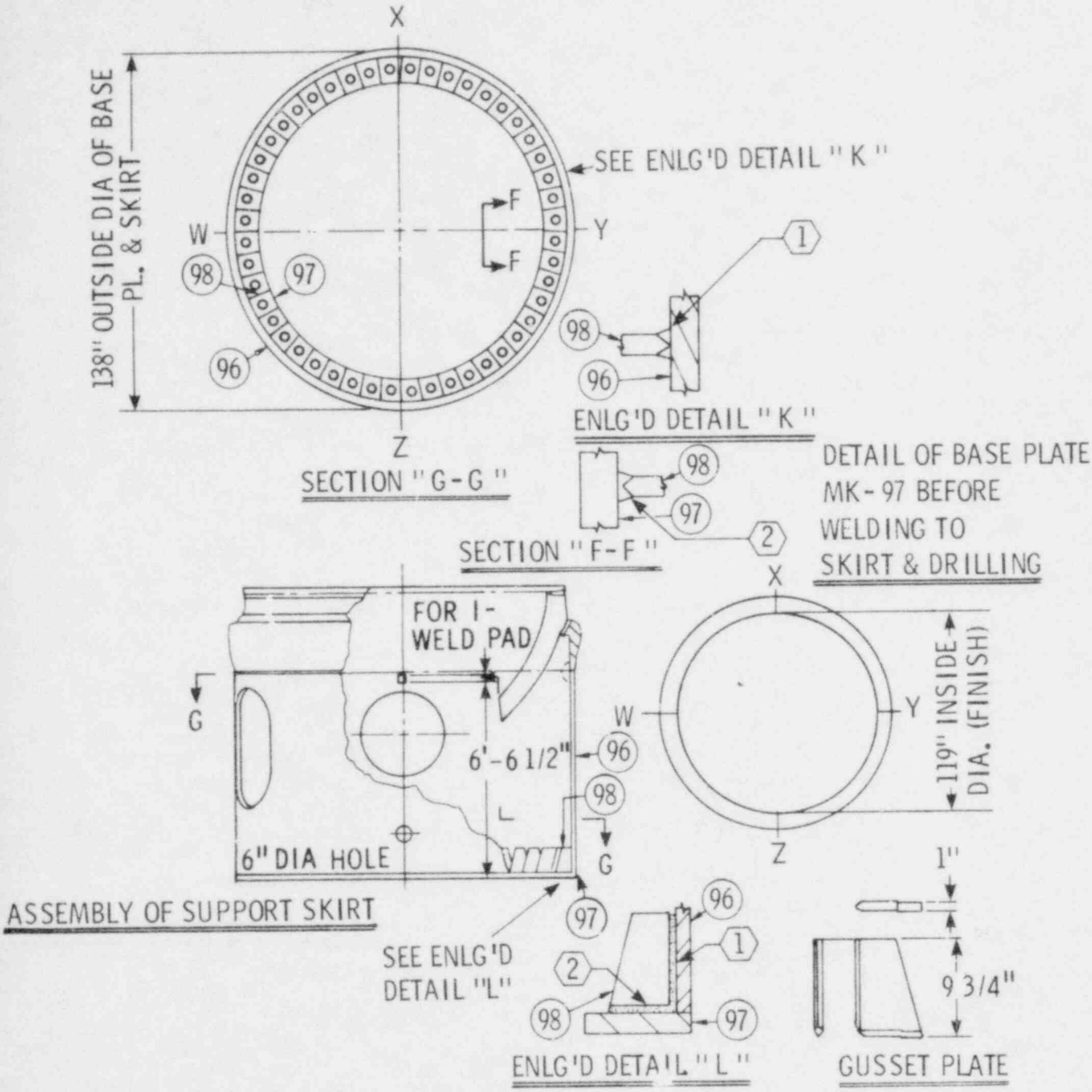


FIG. E15. SKIRT SUPPORT ON THE STEAM GENERATOR OF ARKANSAS NO. 1.

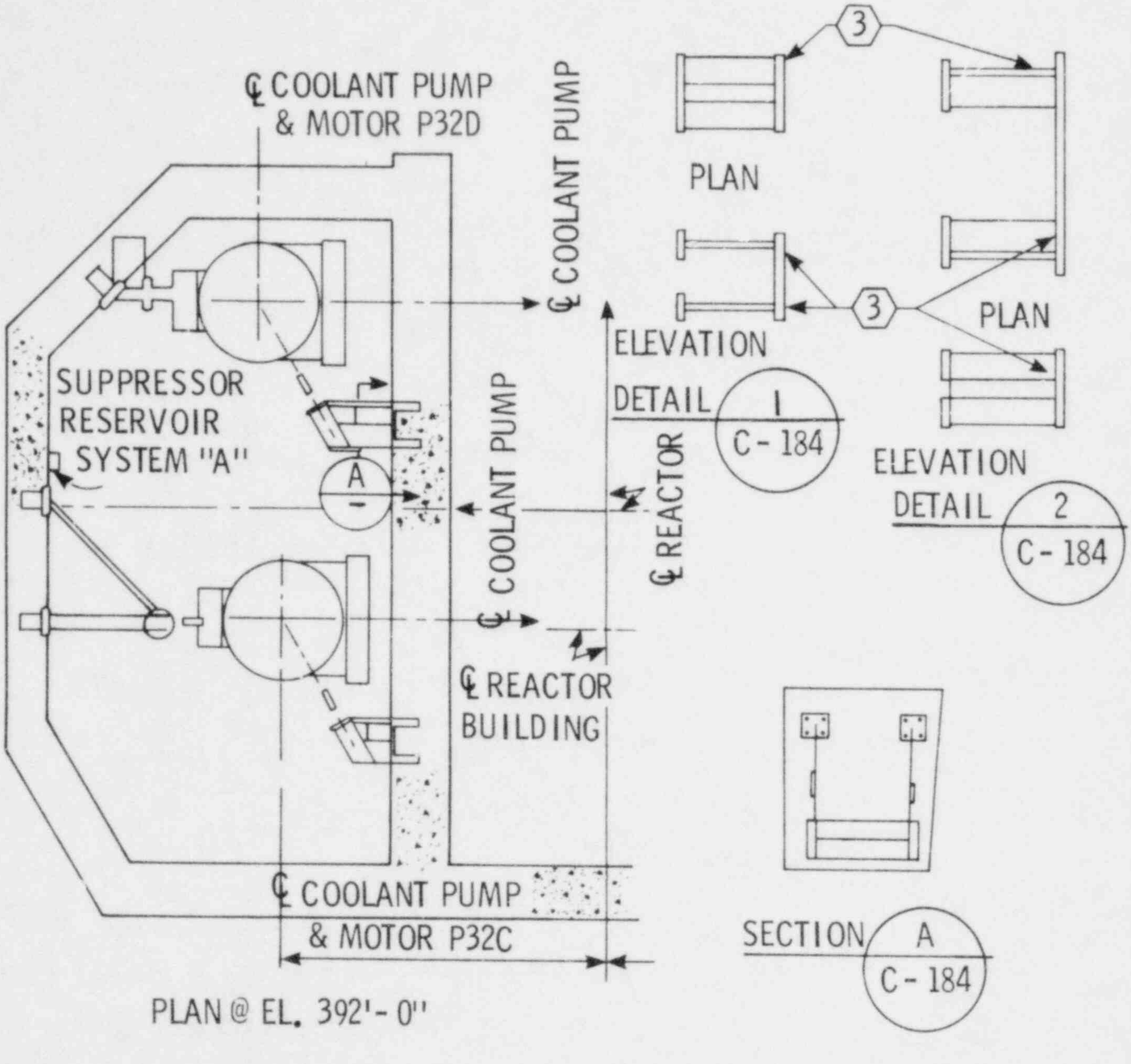


FIG. E16. GENERAL LAYOUT OF THE HORIZONTAL HYDRAULIC SUPPRESSOR SYSTEM FOR THE REACTOR COOLANT PUMP FOR ARKANSAS NO. 1.

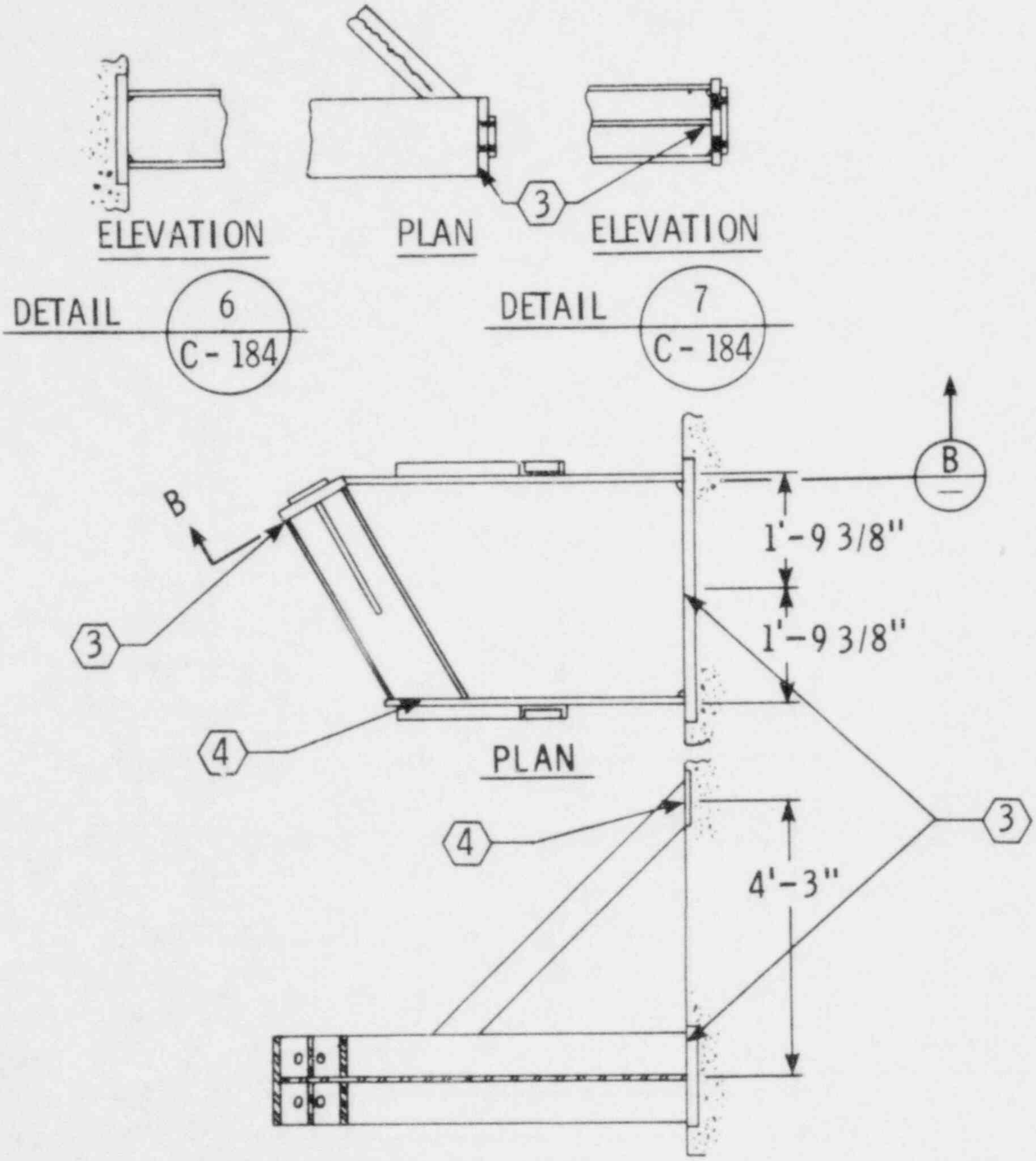


FIGURE E17. JOINT DETAILS REFERENCED IN FIGURE E16

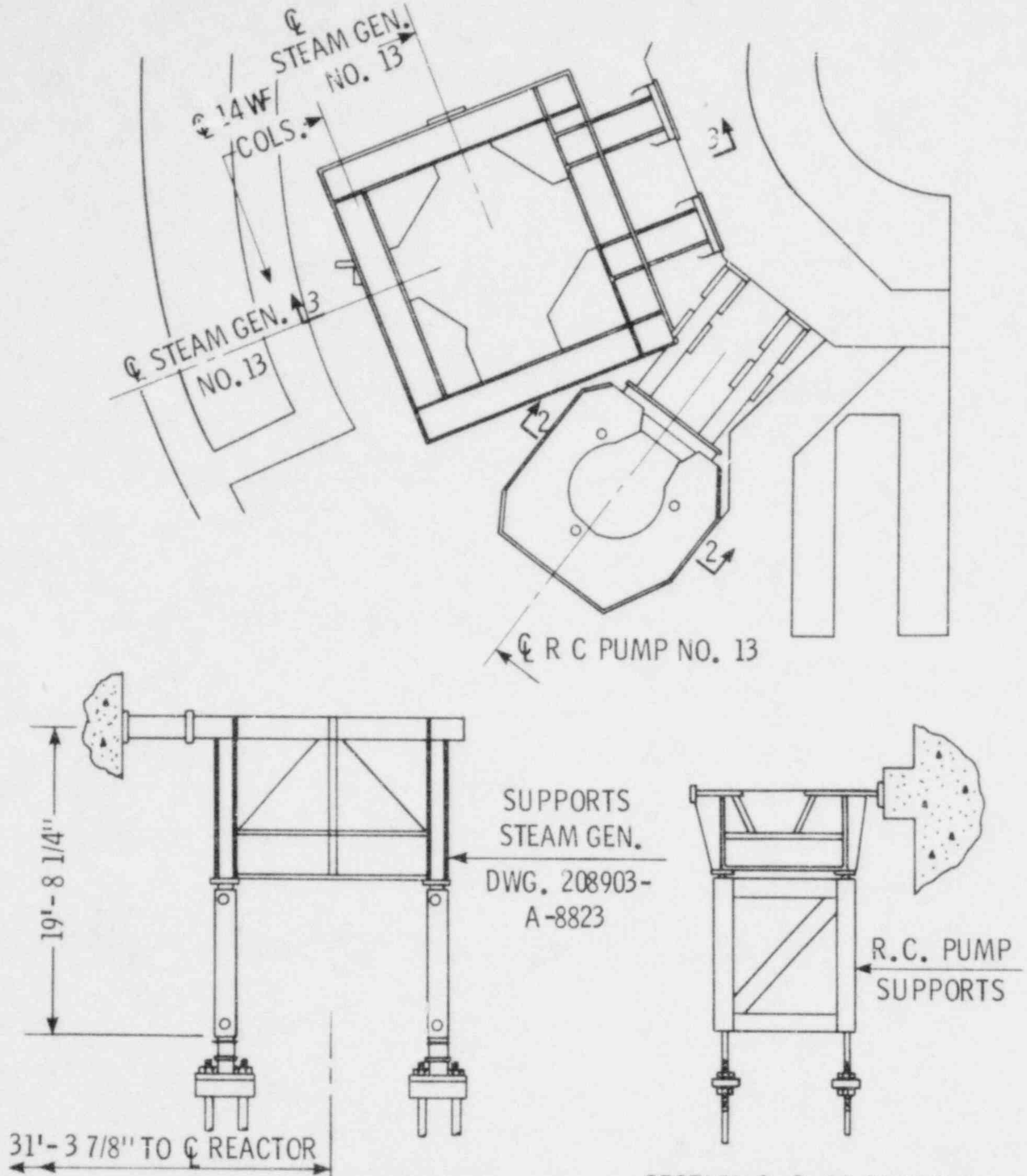


FIGURE E18. PLAN VIEW OF GENERAL LAYOUT AND ELEVATIONS OF STEAM GENERATOR AND REACTOR COOLANT PUMP SUPPORTS FOR SALEM NUCLEAR PLANT.

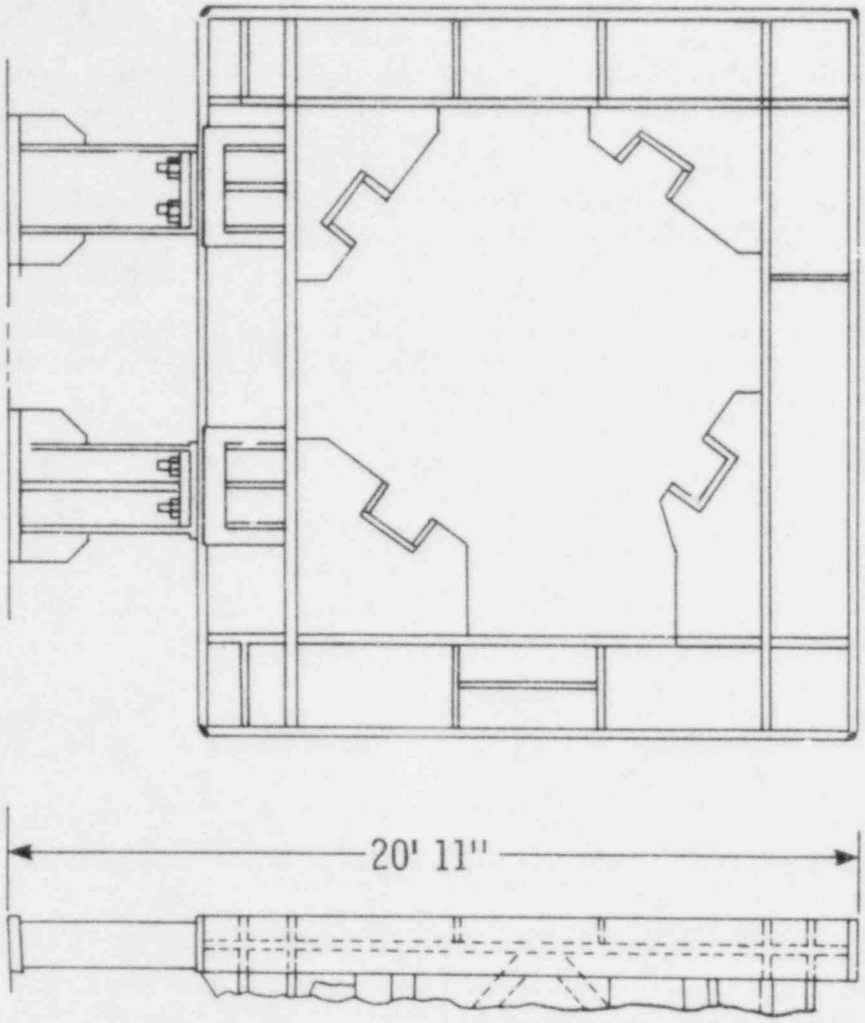


FIGURE E19. DETAILED PLAN VIEW OF STEAM GENERATOR SUPPORT FOR SALEM NUCLEAR PLANT.

APPENDIX F - REFERENCES

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4-2 J. M. Barsom, "Development of the AASHTO Fracture Toughness Requirements for Bridge Steels," Eng. Fract. Mech., 7, (1975), p. 605.

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Annotated Bibliography of Section 5

The following section has been prepared as an aid to a person who wishes to study lamellar tearing in more depth. Perhaps the best way to proceed would be to first read a general survey article, five of which are listed here. Then one might look at the specific topic in which one is most interested. The sources listed here are meant to be an aid in each of the areas but Skinner and Toyama [5.5] have prepared a very complete literature search on lamellar tearing. They have arranged the sources in general topical categories as well as by date of the articles. This reference should be consulted very early in an in-depth study.

A list of topics with references are given below.

Survey Articles (general presentation of the entire topic)

Ref [5.5] 20 p., 413 refs.
[5.6] 67 p., 75 refs.
[5.13] 16 p.
[5.14] 46 p., 33 refs.
[5.16] 12 p., 16 refs.

Test Methods

[5.4]
[5.6] 15 methods explained and illustrated
[5.14], [5.17], [5.18]

Factors which Influence Lamellar Tearing Formation

[5.1], [5.4], [5.6], [5.11], [5.13]

Joint Types Susceptible to Lamellar Tearing

[5.6] 8 types listed
[5.11], [5.13[, [5.16] which is very good.

Methods of Assessing Weld Defects

[5.18], [5.19]

Physics & Metallurgy

[5.1], [5.4], [5.6], [5.7], [5.9], [5.11], [5.14], [5.20], [5.21]

Failures

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APPENDIX D

INFORMATION TO BE REQUESTED FROM GROUP I LICENSEES

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INFORMATION TO BE REQUESTED FROM GROUP I LICENSEES

1. Crystal River Unit 3 - Provide operating temperature of the flange and gusset material (A 515) of the steam generator skirt. Provide state of stress (tension or compression) and magnitude of stress during normal operation and postulated LOCA and safe shutdown earthquake conditions. Provide information regarding the material used and the design of the upper steam generator supports.

2. Davis-Besse Unit 1 - Prior information regarding impact testing of questionable materials was somewhat ambiguous. Clarify whether the impact testing requirement applied to A 36 and A 516 over 5/8 inch thick, or for all materials greater than 5/8 inch thick. For the A 515 and A 53 of the steam generator lower lateral supports, provide state of stress (tensile or compressive) and magnitude of stress during normal operation and postulated LOCA and safe shutdown earthquake conditions.

3. J. M. Farley Units 1 and 2 - Provide information regarding prestress (or lack of it) in the Carpenter Custom 455 steel bolts used in the clevis attachments of the vertical columns.

4. Fort Calhoun - Provide information regarding the significance of the A 307 nuts and bolts to the integrity of the support structures. Provide any information available regarding the properties and testing of the A 307 material.

5. Indian Point Units 2 and 3 - For the A 53 tubing which is used extensively throughout the supports and also for the A 36 plates and shapes, provide (a) operating temperature at various locations, (b) state of stress (tension or compression) and magnitude of stress at the most highly stressed locations in the supports during normal operation and postulated LOCA and safe shutdown earthquake conditions, and (c) section sizes. Provide mill test records for the A 53 and A 36 steels.

6. Kewaunee - For the Vascomax 250 CVM 0.5-inch diameter "Heli-coil screws into S.G." and 1.0-inch diameter "upper support ring girder wall bolts," provide location, and because stress-corrosion cracking of this material is of concern, provide information regarding pre-tension of the heli-coil screws and provide information regarding protective coatings, if used.

7. Maine Yankee - Provide information concerning the heat treatment condition of the steam generator base casting.

8. Millstone Unit 2 - For the A 106 and A 515 steel members in the pump supports, provide (a) locations, (b) range of temperatures at specific locations of (c) below during operation, and (c) state of stress (tension or compression) and magnitude of stress at highly stressed locations of

the A 106 and A 515 members during normal operation and postulated LOCA and safe shutdown earthquake conditions.

9. Palisades - For the A 212 in the base flange of the steam generator supports, provide the temperature during normal operation.

10. Point Beach Units 1 and 2 - For the 12-inches diameter A 53 schedule 100 pipe columns, provide (a) stress state (compression or tension) and stress magnitude at most highly stressed locations during normal operation and under postulated LOCA and safe shutdown earthquake conditions, and (b) temperatures during normal operation at the locations in (a) above.

11. Prairie Island Units 1 and 2 - For the Vascomax 250 CVM 0.5-inch diameter "Heli-coil screws into S.G." and 1.0-inch diameter "upper support ring girder wall bolts" provide location, and because stress-corrosion cracking of this material is of concern, provide information regarding pre-tension of the heli-coil screws and provide information regarding protective coatings, if used.

12. Rancho Seco - Provide additional information regarding the materials and details of construction of the coolant pump horizontal supports. Provide the operating temperature of the A 515 base flange on the steam generator support skirts. Provide information regarding materials and details of design of steam generator upper horizontal restraints.

13. St. Lucie Unit 1 - For the A 515 in the coolant pump snubber clevises, provide (a) temperature during normal operation and (b) state of stress (tension or compression) and magnitude of stress during normal operation and postulated LOCA and safe-shutdown earthquake conditions. Provide information regarding the heat treatment of the A 27 in the steam generator base castings.

14. Surry Units 1 and 2 - Presently being investigated because of concern regarding stress corrosion cracking of Vascomax 300 and 350 steels used extensively throughout all supports. However, for the A 106 pipes, A 285 plates, and A 105 pipe end forgings not presently being reviewed, provide (a) stress state (compression or tension) and stress magnitude at most highly stressed locations (utilizing above steels) during normal operation and under postulated LOCA and safe-shutdown earthquake conditions, and (b) temperature during normal operation at the locations in (a) above.

15. Three Mile Island Unit 1 - Provide additional information regarding the materials and details of construction of the coolant pump horizontal supports. Provide the operating temperature of the A 515 base flange on the steam generator support skirts. Provide information regarding materials and details of design of steam generator horizontal restraints.

16. Yankee Rowe - Provide information regarding the materials and details of design of the upper part of the steam generator support structures. Provide details of construction and materials for the reactor coolant pump hanger rod supports. The A 7 and C 1020 steels are used in the support structures; these are obsolete specifications and the steels can exhibit low fracture toughness. For the locations of these steels, provide (a) temperature during normal operation, and (b) stress state (tension or compression) and magnitude of stress during normal operation and under postulated LOCA and safe-shutdown earthquake conditions.

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16. ABSTRACT (200 words or less)

This report summarizes work performed by the NRC and its contractor, Sandia Laboratories, in resolution of Generic Technical Activity A 12. This task involved determining the possibility of low fracture toughness and lamellar tearing in the materials of pressurized water reactor steam generator and reactor coolant pump supports.

The report describes the technical issues, the technical studies performed by Sandia Laboratories, the NRC staff's technical positions based on these studies, and the staff's plan for implementing its technical positions. It also provides recommendations for further work. The complete Sandia Laboratories input is appended to the report.

17. KEY WORDS AND DOCUMENT ANALYSIS

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