UNCLASSIFIED

NRL Report 8198

Investigation of Warm Prestress for the Case of Small ΔT During a Reactor Loss-of-Coolant Accident

F. J. Loss, R. A. Gray, Jr., and J. R. Hawthorne

Thermostructural Materials Branch
Engineering Materials Division

March 9, 1978

NAVAL RESEARCH LABORATORY
Washington, D.C.

Approved for public release; distribution unlimited.

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for any third party's use or the results of such use of any information, apparatus, product, or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights.

Available from
National Technical Information Service
Springfield, Virginia 22161

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Report 8198	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INVESTIGATION OF WARM PRESTRESS FOR THE CASE OF SMALL ΔT DURING A REACTOR LOSS-OF-COOLANT ACCIDENT		5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL Problem 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) F. J. Loss, R. A. Gray, Jr., and J. R. Hawthorne		8. CONTRACT OR GRANT NUMBER(s) NRL Problem 63M01-40 Project AT(49-24)-0207
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, DC 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Nuclear Regulatory Commission Division of Reactor Safety Research Washington, DC 20555		12. REPORT DATE March 9, 1978 13. NUMBER OF PAGES 25
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

NRC-1 and 5 distributions

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fracture mechanics
Loss-of-coolant accident (LOCA)
Nuclear pressure vessel
Reactor safety
Thermal shock
Warm prestress

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An experimental investigation was conducted to characterize the benefits of warm prestress (WPS) in limiting crack extension in the wall of a nuclear vessel during a loss-of-coolant accident (LOCA) followed by introduction of relatively cold water by the emergency core cooling system. The present research emphasized material behavior under conditions of a small ΔT between the temperature of WPS and the failure temperature as might occur during a LOCA. The results have demonstrated that fracture will not occur during a simultaneous unloading and cooling of the crack-tip region following WPS even

(Continued on back)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued)

though the critical K_{Ic} of the virgin material is achieved. The results also demonstrated that, for the conditions investigated, fracture will not occur unless the level of WPS has been exceeded. It is concluded that WPS produces an "effective" elevation in K_{Ic} and that this elevation will limit crack extension in the vessel wall so as to retain the coolant.

UNCLASSIFIED

CONTENTS

INTRODUCTION 1

APPROACH 3

EXPERIMENTAL INVESTIGATION 5

Material and Specimens 5
Experimental Apparatus 5
Loading Paths 6

K_{Ic} TRENDS 7

WARM-PRESTRESS RESULTS 9

DISCUSSION 13

RELATED RESEARCH TOPICS 14

K_{WPS} Level 14
Irradiated K_{Ic} and K_{IR} Curves 14
Low-Shelf Steel 15

SUMMARY AND CONCLUSIONS 15

ACKNOWLEDGMENTS 16

REFERENCES 16

APPENDIX A — Documentation for the A533-B Class 1 Steel Plate for the Warm-Prestress Test Program 17

APPENDIX B — Statistical Analysis of WPS Effects 22

UNCLASSIFIED

INVESTIGATION OF WARM PRESTRESS FOR THE CASE OF SMALL ΔT DURING A REACTOR LOSS-OF-COOLANT ACCIDENT

INTRODUCTION

A postulated event for a nuclear pressure vessel is a sudden loss-of-coolant accident (LOCA) followed by operation of the emergency core-cooling system (ECCS). (A LOCA is uniquely defined as an instantaneous, double-ended break of a main coolant line to the reactor vessel. The vessel is assumed to be unpressurized following the pipe rupture.) Introduction of the relatively cold ECCS water subjects the hot vessel wall to high thermal stress (thermal shock). If the wall contains a cracklike defect at the inner surface, the stress intensity K_I at the crack tip increases with time to a maximum and then decays as the temperature gradient throughout the wall becomes smaller (Fig. 1). In addition, for highly radiation sensitive materials, neutron bombardment can markedly shift the temperature dependence of the critical fracture toughness K_{Ic} to higher temperatures. With a sufficiently high neutron fluence, the K_I and K_{Ic} curves may intersect as illustrated in Fig. 1. At this point crack initiation would be predicted. It is important that the ensuing crack extension does not completely penetrate the wall, so that the coolant is retained and a possible melting of the reactor core is prevented.

Fortunately, during a LOCA, conditions are such that the crack tip can be subjected to "warm prestress" (WPS). It has been shown [1] that this phenomenon can limit crack extension to prevent complete penetration of the wall. The WPS occurs when the crack-tip region has been loaded to a peak K_I level (Fig. 1), at elevated temperature, that exceeds the critical K_{Ic} value at lower temperatures. The authors have demonstrated [1] that this loading sequence elevates the "effective" fracture toughness of the crack-tip region so that crack extension will not occur when the stress intensity reaches the K_{Ic} value of the virgin metal at the lower temperature. In addition, from physical considerations, one would not expect crack initiation to take place following WPS while K_I decreases with time regardless of whether the K_{Ic} level has been achieved. It can be reasoned that fracture will not occur during this unloading because the resulting decrease of strain at the crack tip eliminates a necessary condition for fracture.

In the preceding investigation [1] the WPS phenomenon during a LOCA was simulated by the mechanical loading of notched, three-point bend specimens. These studies verified the hypothesis that failure does not occur during the period when K_I decreases with time following WPS even though the K_I level exceeds the K_{Ic} of the virgin material. Furthermore it was demonstrated that WPS produces an effective elevation in K_{Ic} whose magnitude depends on the level of WPS, on the magnitude of the ΔT between the temperature of WPS (T_{WPS}) and the failure temperature (T_F) (Fig. 1), and on the amount of unloading of the crack-tip region from the warm prestress level. These studies were used to project the degree of crack extension during a LOCA in a reference calculational model (RCM) [2] of a commercial, pressurized-water reactor vessel. The RCM was used to construct a worst-case condition in terms of a steel that is highly sensitive to radiation coupled with a high fluence

Manuscript submitted December 23, 1977.

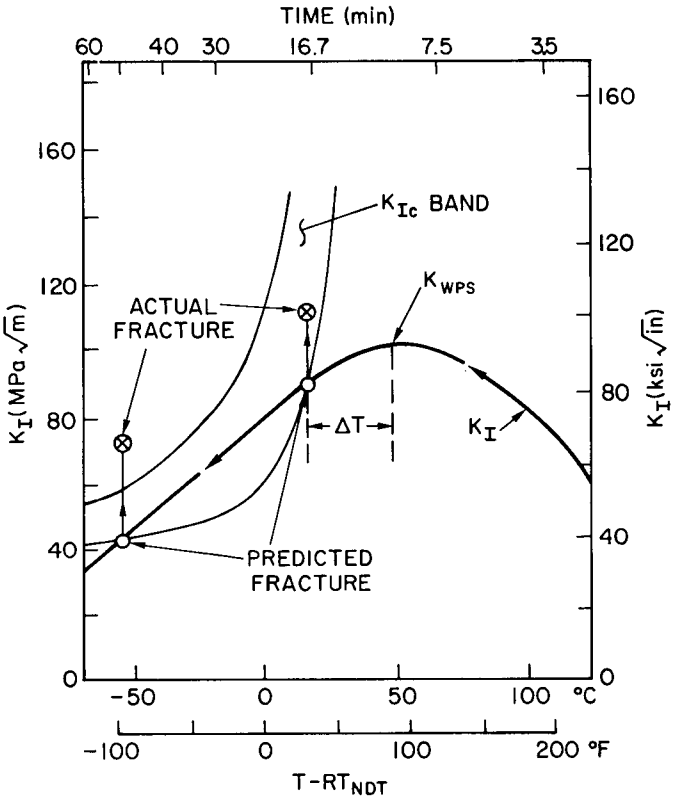

Fig. 1 — Representation of the K_I levels at the tip of a longitudinal flaw in a nuclear pressure vessel during a loss-of-coolant accident followed by operation of the emergency core-cooling system (LOCA-ECCS). The time scale originates with the LOCA. RT_{NDT} is the reference temperature for the material defined in Section III of the ASME Boiler and Pressure Vessel Code. The warm-prestress level (K_{WPS}) is indexed to the maximum K_I achieved during the transient.

level such as encountered near the end of vessel life. Using the WPS phenomenon to interpret calculations of stress intensity for the worst-case RCM performed by Cheverton [2], it was shown that although WPS could not prevent the initiation of shallow flaws, this phenomenon would prevent crack extension from penetrating greater than a depth of 1/3 the vessel wall.

The WPS conditions investigated in the preceding NRL study [1] encompassed a greater range of the variables than would be projected during a LOCA. This was necessary to conclusively demonstrate the effective elevation in K_{Ic} associated with WPS, but in some cases it did subject the material to conditions that were more severe than those during a LOCA. For example, selected specimens were completely unloaded following the attainment of the WPS level, K_{WPS}. This was in contrast to the small, partial unloading actually expected in the vessel (Fig. 1). It was noted that the fracture behavior following the complete unloading resulted in a smaller effective elevation in K_{Ic} than was observed with a partial unloading.

UNCLASSIFIED

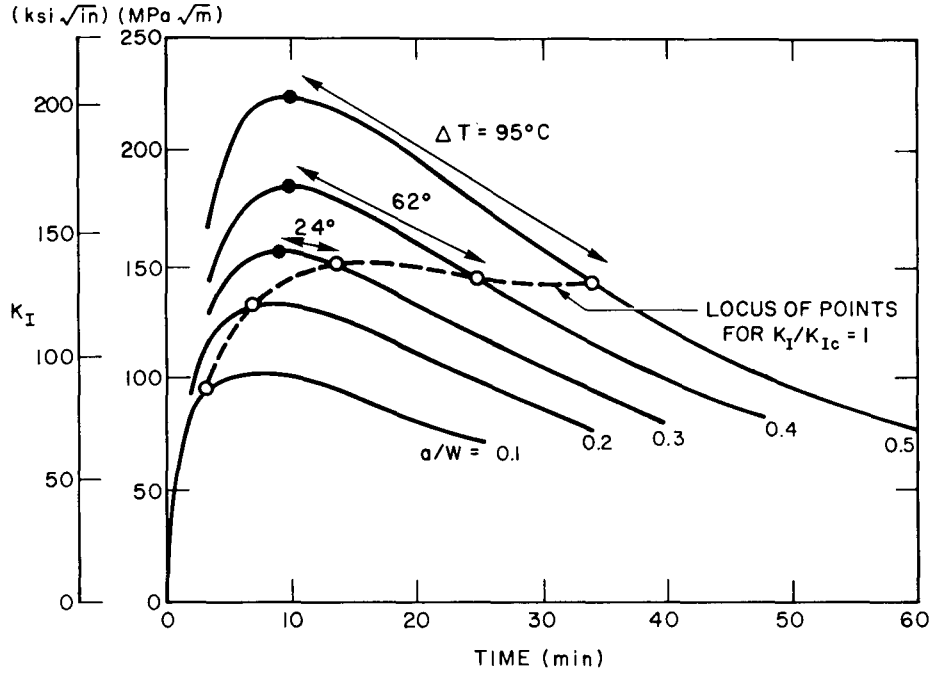

Fig. 2 — Variation of K_I with time for a family of longitudinal flaws of relative depth a/W in a nuclear vessel during a LOCA-ECCS. Warm prestress is effected when the temperature increment ΔT between the point of maximum K_I and the point where K_I intersects K_{Ic} is greater than zero.

In another severe test of the WPS phenomenon, values of ΔT were employed that greatly exceeded those expected during a LOCA. A large ΔT was necessitated by experimental considerations in order to achieve a sufficiently low value of T_F such that a failure level K_F would lie above the K_{Ic} scatterband at that temperature. In this way it was possible to demonstrate the effective K_{Ic} elevation without ambiguity. On the other hand, this procedure also raises questions as to whether a large ΔT introduces other effects that somehow influenced the data to preclude a direct interpretation in terms of LOCA conditions. However, this would not appear to be the case based on an extrapolation of the existing data trends [1], from which it could be projected that WPS tests involving a small ΔT would yield results similar to those obtained with the smallest range of ΔT previously investigated. To verify this hypothesis, a follow-on program was undertaken wherein the WPS tests of the previous study were augmented to include a small ΔT.

APPROACH

Figure 2 illustrates the variation in K_I with time for longitudinal cracks of relative depth a/W in the RCM under the worst-case conditions [3]. For this model ΔT is defined as the temperature difference between the time K_I achieves its maximum value and the time K_I reaches the K_{Ic} level. The figure shows that ΔT can vary from a minimum of 0°C at a relative crack depth of 0.2 to approximately 95°C at a relative depth of 0.5. In other words there exists no "typical" ΔT. Of course WPS is effected only for values of ΔT that are greater than zero. As part of the preceding study [1] the smallest value of ΔT imposed on

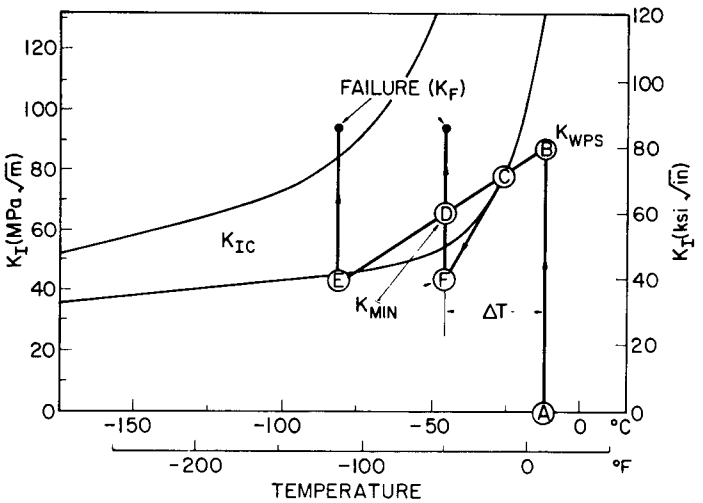

Fig. 3 — Failure paths for warm prestress specimens involving a small ΔT, which is representative of the crack-tip behavior during a LOCA-ECCS.

the material was approximately 95°C, which corresponds to a very deep crack in the vessel. The goal of the present study was to impose a ΔT as small as practical to simulate the behavior of a crack whose initial depth lies between an a/W of 0.2 and 0.5.

As shown in Fig. 3, it is difficult to impose a very small ΔT. That is, the specimen first must be loaded at a temperature close to the lower bound of the K_{Ic} band (path AB). If this boundary has not been accurately defined, premature failure may result upon loading to the desired value of K_{WPS}. The smallest ΔT that can be achieved experimentally is therefore established by the difference between the lowest temperature at which the specimen can be successfully loaded to K_{WPS} and the highest temperature at which K_I first intersects the K_{Ic} band (ΔT corresponding to path BC). Unfortunately, if failure does not occur when the K_{Ic} level is reached under the preceding loading sequence, it is not possible to state whether this desirable outcome was due to the expected elevation of "effective" K_{Ic} by the WPS or whether it was due to the fact that in the absence of WPS this particular specimen would have failed near the upper bound of the K_{Ic} band. A statistically designed experimental program might resolve this uncertainty and identify the confidence one has in the WPS being the cause.

Instead of developing a statistical program, it was decided to impose several values of ΔT that would produce failures both within the K_{Ic} scatterband (path BD) as well as beyond the limits of the K_{Ic} upper bound (path BE). Failures in the latter region would demonstrate with less ambiguity the effective elevation in K_{Ic} attributable to WPS. With respect to failures within the K_{Ic} scatterband, paths having various degrees of unloading from K_{WPS} (such as BCD and BCF in Fig. 3) were chosen to demonstrate that failure never occurs during unloading even though the K_{Ic} level is reached and that the failures always occur above the K_{WPS} level. The latter result would support the conclusion that the effective elevation in K_{Ic} does occur in the presence of a small ΔT. With sufficient failures within the K_{Ic} scatterband to demonstrate the preceding trend, it would also be possible to perform statistical analyses to further support the conclusion with respect to this region.

UNCLASSIFIED

One objective of the experimental approach was to subject three-point bend specimens to a K_{WPS} level that did not exceed the K_{Ic} measurement capacity of the specimen according to ASTM Standard E-399. It was felt that this restriction limits the crack-tip plastic zone to a size no larger than that exhibited in a thick vessel wall. In this way any benefit attributed to the WPS phenomenon would not be subjected to the uncertainty that might arise if the simulated vessel loading produced a plastic zone larger than that in the vessel wall during a LOCA at the same level of K_{WPS}. However this restriction in K_{WPS} level precludes the investigation of higher values of K_{WPS} that may occur during a LOCA (Fig. 2).

From the previous WPS investigation [1] it was determined that 30°C is the smallest ΔT that could be imposed successfully. Consequently this ΔT increment became a prime objective of the present investigation. The results from the earlier study also demonstrated that the specimen unloading path, wherein both the load and temperature are decreased simultaneously, produced no trends in the data as long as the degree of unloading from the K_{WPS} level remained constant. Therefore a linear unloading path was chosen. Two values of unloading were employed to produce K_{min}/K_{WPS} ratios of 0.5 and 0.75, where K_{min} is the minimum value of K_I during the unloading. As seen from the decrease in K_I associated with the ΔT increments in Fig. 2, this unloading is somewhat larger than would actually occur during a LOCA. However it has been demonstrated [1] that an overestimate of the actual unloading associated with a LOCA will lead to a conservative interpretation with respect to the effective K_{Ic} elevation.

EXPERIMENTAL INVESTIGATION

Material and Specimens

The test specimens were machined from an A533-B1 steel plate 210 mm (8-1/4 in.) thick. The plate was specially purchased for this program to specifications currently used for nuclear pressure vessel construction. The plate properties are described in Appendix A. Specimens 76 mm (3 in.) thick were cut in the TL orientation. Two specimens were taken from the plate thickness, so that one surface of each corresponded to the plate midthickness (½T). The plate exhibited essentially uniform properties throughout the thickness from which WPS specimens were removed (Appendix A). Three-point bend specimens were machined to ASTM E-399 proportions with a span-to-width (S/W) ratio of 4.0. Each specimen was fatigue precracked at a maximum K_I level of 27 MPa$\sqrt{m}$ (25 ksi$\sqrt{in.}$) and for a distance of 6 mm (1/4 in.) to provide an overall crack-depth-to-width ratio (a/W) of 0.50.

Experimental Apparatus

The specimens were loaded on a three-point bend fixture having roller supports at the outer edges (Fig. 4). The fixture was surrounded by a cooling bath that was used to control the specimen temperature. The temperature was monitored by means of a thermocouple spot-welded to the specimen. Care was taken during cooling so that temperature differences throughout the specimen would be only a few degrees Celsius. Thus any thermal stresses during cooling did not significantly influence the crack-tip K level as computed from the mechanical loading.

Fig. 4 — Specimen and loading fixture used to conduct the WPS experiments. The cooling bath has been removed to highlight the placement of the clip gage and LVDTs used to monitor the crack mouth opening and midspan development respectively. Also removed were two bars spanning the two roller supports to which the LVDT cores were attached.

Two linear variable differential transformers (LVDT), one on either side of the specimen, were summed to monitor specimen deflections. As needed to compute the applied level of the J integral at fracture, each LVDT was attached to both the midspan loading ram and to a bar that was placed across the two specimen outer-roller supports. Of course the jig deflection was accounted for in computation of the J integral. A clip gage was attached to knife edges near the crack mouth in order to monitor crack mouth opening (CMO) vs specimen load as required for the computation of K_{Ic}.

Loading Paths

The specimen loading sequence was designed to simulate a typical K_I-vs-temperature path of the crack-tip region as shown in Fig. 1. Warm prestressing was accomplished by slowly loading each specimen at a fixed temperature to the desired level of K_{WPS}. At this point both the load and temperature were simultaneously decreased along the paths illustrated schematically in Fig. 3. Then at a predetermined temperature corresponding to K_{min} the specimen was isothermally loaded to failure. The absolute temperatures used in this program were much lower than those which would occur during a LOCA. With a LOCA it is assumed that the K_I-vs-temperature trend has been markedly elevated as a result of the neutron bombardment during service. Since the present program used unirradiated material, an effective increase in K_{Ic} due to WPS could be demonstrated only at low temperatures, where the material behaves in a linear-elastic manner.

UNCLASSIFIED

One objective of the experimental approach was to subject three-point bend specimens to a K_{WPS} level that did not exceed the K_{Ic} measurement capacity of the specimen according to ASTM Standard E-399. It was felt that this restriction limits the crack-tip plastic zone to a size no larger than that exhibited in a thick vessel wall. In this way any benefit attributed to the WPS phenomenon would not be subjected to the uncertainty that might arise if the simulated vessel loading produced a plastic zone larger than that in the vessel wall during a LOCA at the same level of K_{WPS}. However this restriction in K_{WPS} level precludes the investigation of higher values of K_{WPS} that may occur during a LOCA (Fig. 2).

From the previous WPS investigation [1] it was determined that 30°C is the smallest ΔT that could be imposed successfully. Consequently this ΔT increment became a prime objective of the present investigation. The results from the earlier study also demonstrated that the specimen unloading path, wherein both the load and temperature are decreased simultaneously, produced no trends in the data as long as the degree of unloading from the K_{WPS} level remained constant. Therefore a linear unloading path was chosen. Two values of unloading were employed to produce K_{min}/K_{WPS} ratios of 0.5 and 0.75, where K_{min} is the minimum value of K_I during the unloading. As seen from the decrease in K_I associated with the ΔT increments in Fig. 2, this unloading is somewhat larger than would actually occur during a LOCA. However it has been demonstrated [1] that an overestimate of the actual unloading associated with a LOCA will lead to a conservative interpretation with respect to the effective K_{Ic} elevation.

EXPERIMENTAL INVESTIGATION

Material and Specimens

The test specimens were machined from an A533-B1 steel plate 210 mm (8-1/4 in.) thick. The plate was specially purchased for this program to specifications currently used for nuclear pressure vessel construction. The plate properties are described in Appendix A. Specimens 76 mm (3 in.) thick were cut in the TL orientation. Two specimens were taken from the plate thickness, so that one surface of each corresponded to the plate midthickness (½T). The plate exhibited essentially uniform properties throughout the thickness from which WPS specimens were removed (Appendix A). Three-point bend specimens were machined to ASTM E-399 proportions with a span-to-width (S/W) ratio of 4.0. Each specimen was fatigue precracked at a maximum K_I level of 27 MPa$\sqrt{m}$ (25 ksi$\sqrt{in.}$) and for a distance of 6 mm (1/4 in.) to provide an overall crack-depth-to-width ratio (a/W) of 0.50.

Experimental Apparatus

The specimens were loaded on a three-point bend fixture having roller supports at the outer edges (Fig. 4). The fixture was surrounded by a cooling bath that was used to control the specimen temperature. The temperature was monitored by means of a thermocouple spot-welded to the specimen. Care was taken during cooling so that temperature differences throughout the specimen would be only a few degrees Celsius. Thus any thermal stresses during cooling did not significantly influence the crack-tip K level as computed from the mechanical loading.

Fig. 4 — Specimen and loading fixture used to conduct the WPS experiments. The cooling bath has been removed to highlight the placement of the clip gage and LVDTs used to monitor the crack mouth opening and midspan development respectively. Also removed were two bars spanning the two roller supports to which the LVDT cores were attached.

Two linear variable differential transformers (LVDT), one on either side of the specimen, were summed to monitor specimen deflections. As needed to compute the applied level of the J integral at fracture, each LVDT was attached to both the midspan loading ram and to a bar that was placed across the two specimen outer-roller supports. Of course the jig deflection was accounted for in computation of the J integral. A clip gage was attached to knife edges near the crack mouth in order to monitor crack mouth opening (CMO) vs specimen load as required for the computation of K_{Ic}.

Loading Paths

The specimen loading sequence was designed to simulate a typical K_I-vs-temperature path of the crack-tip region as shown in Fig. 1. Warm prestressing was accomplished by slowly loading each specimen at a fixed temperature to the desired level of K_{WPS}. At this point both the load and temperature were simultaneously decreased along the paths illustrated schematically in Fig. 3. Then at a predetermined temperature corresponding to K_{min} the specimen was isothermally loaded to failure. The absolute temperatures used in this program were much lower than those which would occur during a LOCA. With a LOCA it is assumed that the K_I-vs-temperature trend has been markedly elevated as a result of the neutron bombardment during service. Since the present program used unirradiated material, an effective increase in K_{Ic} due to WPS could be demonstrated only at low temperatures, where the material behaves in a linear-elastic manner.

UNCLASSIFIED

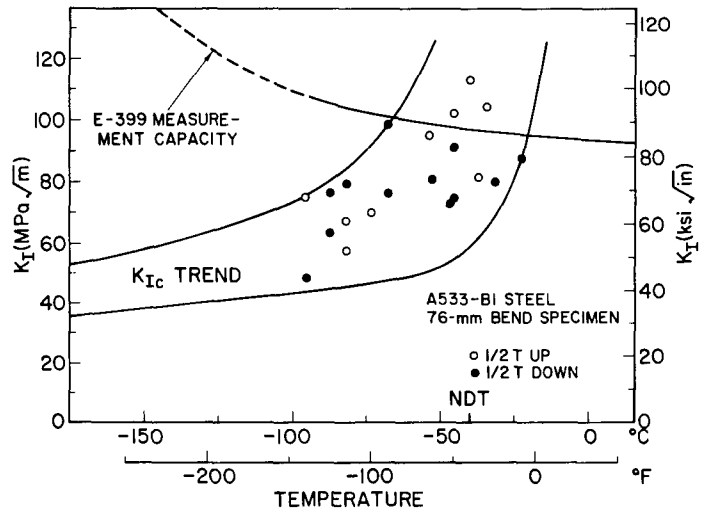

Fig. 5 — K_{Ic} trends for the program material. The shapes of the upper and lower boundaries of the scatterband are based on K_{Ic} data for a different heat of A533-B1 steel [1] that encompass a larger temperature range from that investigated in the present study.

For the majority of the specimens the K_{WPS} level was limited to 88 MPa$\sqrt{m}$ (80 ksi$\sqrt{in.}$), since this is the maximum K_I level that could be applied without violation of the specimen thickness requirements of ASTM E-399. However a few specimens were "overloaded" to a K_{WPS} level of 125 MPa$\sqrt{m}$ (113 ksi$\sqrt{in.}$). This load is equivalent to the ASTM-allowable value for a specimen 150 mm (6 in.) thick. Since the previous study [1] has suggested that no detrimental effects result from the overloading, this scheme was used to demonstrate the benefits of WPS at higher levels of K_I which also can be encountered during a LOCA.

K_{Ic} TRENDS

It is essential to characterize the K_{Ic} trends of the material used in this program in order to permit assessment of the effective elevation in K_{Ic} attributable to WPS. The K_{Ic} behavior as a function of temperature was determined with 76-mm-thick specimens that were identical to those used for the WPS tests. The results are illustrated in Fig. 5 and also listed in Table 1. Specimens were cut from the same plate-thickness positions as the WPS specimens. The data in Fig. 5 appear to exhibit no trend due to thickness location. This observation supports the conclusions reached in Appendix A concerning the through-thickness uniformity of the mechanical properties.

The K_{Ic} scatterband may seem large, but it is essentially identical to that exhibited by the A533-B1 plate (HSST-02) used in the preceding investigation [1] when account is taken of the additional K_{Ic} data developed by NRL in that study. In fact the data in Fig. 5 were found to lie exactly within the scatterband for the preceding investigation with normalized to the NDT temperature. Consequently the scatterband from the HSST-02 plate, which covers a larger temperature range than the present study, was used to define the shape of

Table 1 — K_{Ic} Date for 76-mm Bend Specimens

Specimen Number	Location*	Temperature °C	Temperature °F	a/W	P_{max}† kg	P_{max}† lb	K_Q MPa√m	K_Q ksi√in.	E-399 Thickness Valid	K_{Jc}‡ MPa√m	K_{Jc}‡ ksi√in.
W7-12	A	-96	[illegible]	0.508	21045	16300	75.3	68.5	Yes		
W7-40	B	-95	-139	0.507	13682	30100	48.6	44.2	Yes		
W7-42	B	-87	[illegible]	0.508	21455	17200	76.7	69.8	Yes		
W7-38	B	-87	[illegible]	0.509	17652	[illegible]	63.4	57.7	Yes		
W7-20	A	-82	[illegible]	0.506	19045	11900	67.6	61.5	Yes		
W7-39	B	-82	[illegible]	[illegible]	22273	19000	79.7	72.[illegible]	Yes		
W7-15	A	-82	[illegible]	[illegible]	16136	[illegible]	57.7	52.[illegible]	Yes		
W7-10	A	-73	[illegible]	[illegible]	19591	[illegible]	70.3	6[illegible].9	Yes		
W7-37	B	-65	-99	[illegible]	21364	[illegible]	75.9	69.[illegible]	Yes		
W7-36	B	-66	[illegible]	[illegible]	27727	[illegible]	98.6	[illegible]	No	98.5	[illegible]
W7-[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	26682	[illegible]	95.0	[illegible]	No	95.0	[illegible]
W[illegible]	B	-52	[illegible]	[illegible]	22[illegible]01	[illegible]	81.0	[illegible]	Yes		
W[illegible]	B	-45	[illegible]	[illegible]	[illegible]	[illegible]	72.[illegible]	[illegible]	Yes		
W[illegible]	A	-40	[illegible]	[illegible]	2[illegible]	[illegible]	102.2	[illegible]	No	102.2	[illegible]
W[illegible]	B	-45	[illegible]	[illegible]	[illegible]	[illegible]	91.2	[illegible]	No	91.2	[illegible]
W[illegible]	B	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	74.7	[illegible]	Yes		
W[illegible]	A	-40	[illegible]	[illegible]	30909	[illegible]	109.9	[illegible]	No	113.1	[illegible]
W[illegible]	A	-37	[illegible]	[illegible]	22518	[illegible]	83.1	[illegible]	Yes		
W[illegible]	A	-31	[illegible]	[illegible]	29273	[illegible]	101.4	[illegible]	No	104.4	[illegible]
W[illegible]	B	-32	[illegible]	[illegible]	22560	[illegible]	80.4	73.2	Yes		
W[illegible]	B	-23	[illegible]	[illegible]	21109	[illegible]	87.6	79.7	Yes		

*A = ½T up; B = ½T down.
†$P_{max} = P_Q$ for all tests.
‡K_{Ic} computed from the J integral (Eq. 1), as discussed in the text following reference to this table.

the upper and lower scatterbands for the present data beyond the range of temperatures investigated.

A few of the data points shown in Fig. 5 violate the E-399 thickness requirement. The K_{Ic} values for these specimens (Table 1) were therefore computed from the J-integral value at the point of maximum load (K_{Jc}) from the relationship

$$K_{Jc}^2 = E\,J_{Ic}, \tag{1}$$

where E is the elastic modulus.

Since the fractures propagated in a cleavage (brittle) mode starting from the fatigue precrack, the J value computed on the basis of maximum failure load represents the initiation value J_{Ic}. In other words there existed no stable crack extension with rising load that is often associated with elastic-plastic fractures.

All except the highest datum in Fig. 5 exhibited a sufficiently linear correspondence between load and CMO to meet the 5% secant offset requirement of E-399. Because of this linearity, the K_{Ic} value computed from the J integral corresponds almost exactly to the K_Q value computed from E-399 rules on the basis of maximum load, as one would expect. For

UNCLASSIFIED

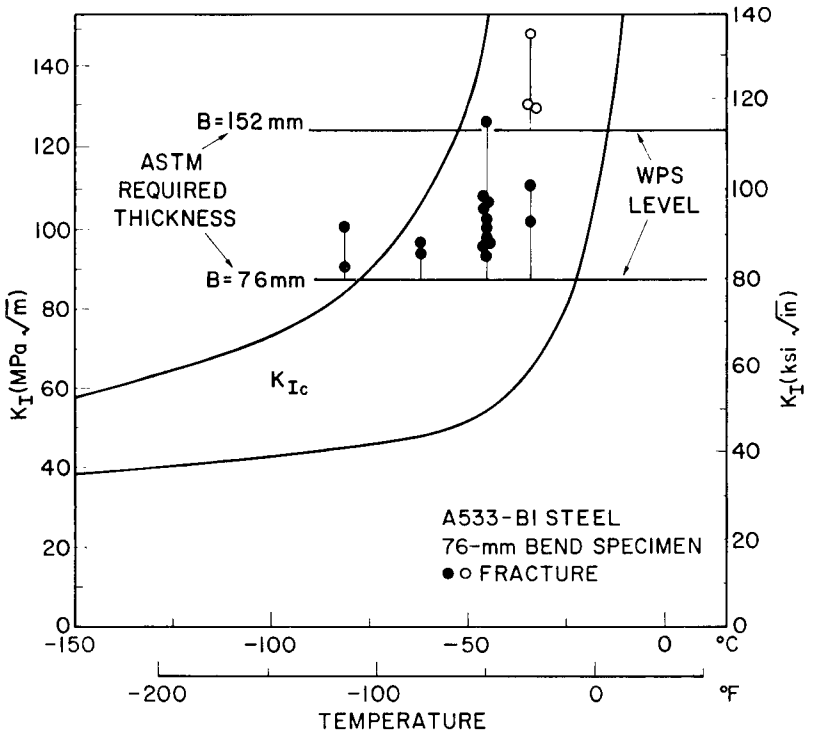

Fig. 6 — Results of WPS experiments involving a small ΔT. All failures are above the level of WPS that was imposed at a higher temperature.

these data, only the thickness requirement of E-399 was violated. If one accepts that K_{Ic} can be computed from the J integral by Eq. 1, then the linear-load-vs-deflection record appears to be a sufficient condition to define a "valid" K_{Ic} value irrespective of the E-399 thickness requirement.

For only the highest datum in Fig. 4 did the load-vs-CMO record exhibit sufficient curvature to violate the 5% secant rule prior to fracture. In this case the K_{Jc} value was only 3% higher than that computed from the E-399 rules using the maximum load. Thus it is concluded that the "invalid" points in Fig. 5 are essentially identical to those that would have been determined by larger specimens of the required thickness.

WARM-PRESTRESS RESULTS

Results of the WPS experiments are presented in Fig. 6 and Table 2. The majority of the specimens were loaded to a K_{WPS} of 88 MPa$\sqrt{m}$ (80 ksi$\sqrt{in.}$). This K_{WPS} level is the highest that would be permitted in terms of K_{Ic} measurement capacity defined by E-399. The failure paths followed those illustrated schematically in Fig. 3; the exact paths are defined by the temperatures and K_I levels listed in Table 2. The specimens were approximately equally divided between a 25% and a 50% unloading from the K_{WPS} level. Various ΔT increments were employed ranging from 22 to 50°C (40 to 90°F), but the majority of tests were conducted with a ΔT of 33°C (60°F). Three specimens were subjected to a K_{WPS} "overload" to a level of 124 MPa$\sqrt{m}$ (113 ksi$\sqrt{in.}$). This is the K_I level which would have been permitted by E-399 for a specimen 150 mm (6 in.) thick.

Table 2 — Warm-Prestress (WPS) Data for 76-mm Bend Specimens

Specimen Number	WPS			Minimum			Failure			ΔT* (°C)	$\frac{K_{min}}{K_{WPS}}$	$\frac{K_F}{K_{WPS}}$
	Temp. (°C)	Load (kg)	K_{WPS} (MPa$\sqrt{m}$)	Temp. (°C)	Load (kg)	K_{min} (MPa$\sqrt{m}$)	Temp. (°C)	Load (kg)	K_F (MPa$\sqrt{m}$)			
W7-6	-12	24636	88.1	-34	18477	66.0	-34	31136	111.3	22	0.75	1.26
W7-7	-12	24636	87.8	-34	12318	43.8	-34	28682	102.2	22	0.50	1.16
W7-9	-12	24636	88.6	-46	10455	37.6	-46	26000	93.5	33	0.42	1.06
W7-14	-12	24818	89.1	-46	18272	65.6	-46	26727	95.9	33	0.74	1.08
W7-8	-12	24682	88.5	-46	18273	65.5	-46	29864	107.0	33	0.74	1.21
W7-35	-12	24636	88.1	-46	18455	65.9	-46	28727	102.7	33	0.75	1.17
W7-34	-12	24636	88.1	-46	12318	44.1	-46	30364	108.6	33	0.50	1.23
W7-26	-12	24636	87.8	-46	11409	40.7	-46	29591	105.5	33	0.46	1.20
W7-3	-12	24682	88.7	-46	18455	66.4	-46	28091	101.0	33	0.75	1.14
W7-28	-12	24636	88.3	-46	18409	66.0	-46	27455	98.5	33	0.75	1.11
W7-2	-12	24636	89.0	-46	12318	44.5	-46	26727	96.6	33	0.50	1.08
W7-24	-12	24818	88.1	-46	12545	44.5	-46	35636	126.6	33	0.51	1.44
W7-30	-32	24636	88.3	-62	12181	43.7	-62	26363	94.6	30	0.49	1.07
W7-27	-12	27455	87.5	-62	18455	65.5	-62	27455	97.5	50	0.75	1.11
W7-17	-54	24090	88.5	-82	11090	39.3	-82	25636	91.0	28	0.46	1.06
W7-21	-54	24090	85.8	-82	9773	34.8	-82	28364	101.1	28	0.41	1.18
W7-1	-1	34864	126.0	-34	17273	63.4	-34	36091	130.5	33	0.50	1.04
W7-5	-1	35091	126.4	-34	26318	94.8	-34	36273	130.7	33	0.75	1.03
W7-25	-1	35273	125.8	-34	17636	63.0	-34	41727	148.9	33	0.50	1.18

*$\Delta T = T_{WPS} - T_F$.

For specimens loaded to a K_{WPS} level of 88 MPa$\sqrt{m}$ (80 ksi$\sqrt{in.}$), the load-vs-CMO records exhibited a slight curvature, but they were sufficiently linear to fall within a 5% secant construction line as required by E-399 rules for analysis of K_{Ic} tests. For specimens reloaded to failure at T_F, all records initially exhibited a better linearity than was first recorded. This linearity extended to approximately 10% above the WPS load (P_{WPS}). Above 1.1 P_{WPS} the records displayed a curvature that appeared to be a continuation of the initial loading at T_{WPS}. For specimens loaded to the higher K_{WPS} level of 124 MPa$\sqrt{m}$ (113 ksi$\sqrt{in.}$) the curvature of the initial-load-vs-CMO records was sufficient to violate the 5% secant line by a small margin. For all specimens the fracture appearance was completely brittle with no evidence of ductile tearing adjacent to the fatigue precrack. This appearance is identical to that illustrated in Ref. 1.

Two observations from the results shown in Fig. 6 summarize the essence of this investigation:

- No specimens failed during the simultaneous unloading and cooling even though the critical K_{Ic} for the virgin material was attained;
- Without exception, the failure levels exceeded the level of warm prestress.

With respect to the first observation, it was expected from physical reasoning that failure would not take place during unloading and cooling even though the K_{Ic} level was reached. This behavior is consistent with that observed during the previous investigation [1] and is believed to result from the fact that the decreasing level of strain at the crack tip during

UNCLASSIFIED

unloading removes a necessary condition for fracture. The second observation, that of a failure level greater than K_{WPS}, is also consistent with a projection of the trends evolved in the preceding study.

Because of the small ΔT values employed in the present investigation, both the K_{min} and K_F values were forced to lie within the K_{Ic} scatterband. This fact projects a degree of uncertainty with respect to interpretation of the effective elevation in K_{Ic} by WPS. For example, it could be postulated that the K_{Ic} level for a given specimen was not actually achieved during the partial unloading when the K_{min} lies within, or even below, the K_{Ic} scatterband (such as at point D in Fig. 3). This hypothesis is expected to be correct for some specimens, but it is unlikely to apply to all the WPS tests. Consequently the first of the two preceding observations would appear to be valid.

With respect to the failures illustrated in Fig. 6, all but two lie within the K_{Ic} scatterband. Thus a statistical analysis is required in order to more confidently conclude whether the failure levels above K_{WPS} were the result of an effective elevation in K_{Ic} due to WPS or the result of K_I fractures that normally would have exceeded the K_{WPS} in the absence of WPS. For example all but one of the ten failures at -46°C lie close to one another. The one datum which exhibits a K_F near the upper K_{Ic} boundary (and possibly others) is therefore believed to have resulted from an inherently high toughness, so that its failure level does not reflect the influence of WPS. Considering the load-vs-CMO behavior previously described, it is possible that the extended linear behavior beyond P_{WPS} was a reflection of the effective K_{Ic} elevation due to WPS, whereas the failures above 1.1 P_{WPS} resulted partly from a high toughness that would have produced failure at the measured level with a virgin specimen. However, the lack of scatter otherwise exhibited by the data at -46°C is considered significant, since this is not typical of the large scatter observed with the K_{Ic} tests of virgin material (Fig. 5). Thus it is reasonable to infer that although WPS may not elevate the toughness of a material whose K_{Ic} would be greater than K_{WPS}, it will produce an effective K_{Ic} elevation in material of lower toughness, so that a value less than K_{WPS} will not be observed.

Two WPS fractures in Fig. 6 lie above the K_{Ic} upper boundary. In this case one might conclude that the effective elevation in K_{Ic} due to WPS has been positively demonstrated. This is not necessarily correct, since the boundaries of the K_{Ic} data in Fig. 5 do not encompass the 99% confidence limit. It has been shown by regression analysis [4] that the width of the K_{Ic} scatterband at a level of 88 MPa$\sqrt{m}$ would be over 110°C (200°F); this is twice as great as the scatter defined in Fig. 5.

To clarify the uncertainty in the data described above, statistical analyses of the data have been performed (Appendix B). It was assumed that the median of the K_{Ic} data (Fig. 5) passes through 88 MPa$\sqrt{m}$ at -46°C. It is observed that this temperature is the same as the failure temperature for ten specimens illustrated in Fig. 6. Under the above assumption, it is concluded that in the absence of WPS (the null hypothesis) the probability is better than 99% that at least one of the ten failures at -46°C should have been less than 88 MPa$\sqrt{m}$. (In statistical terminology the observed significance level is less than 1%.) Since all of the failures at this temperature were higher than 88 MPa$\sqrt{m}$, it is concluded that this result must be due to the effects of WPS (the absence of WPS is rejected).

In the prior investigation [1] several specimens received a K_{WPS} "overload" to the level permitted for 150-mm-thick specimens. The behavior of those specimens was no

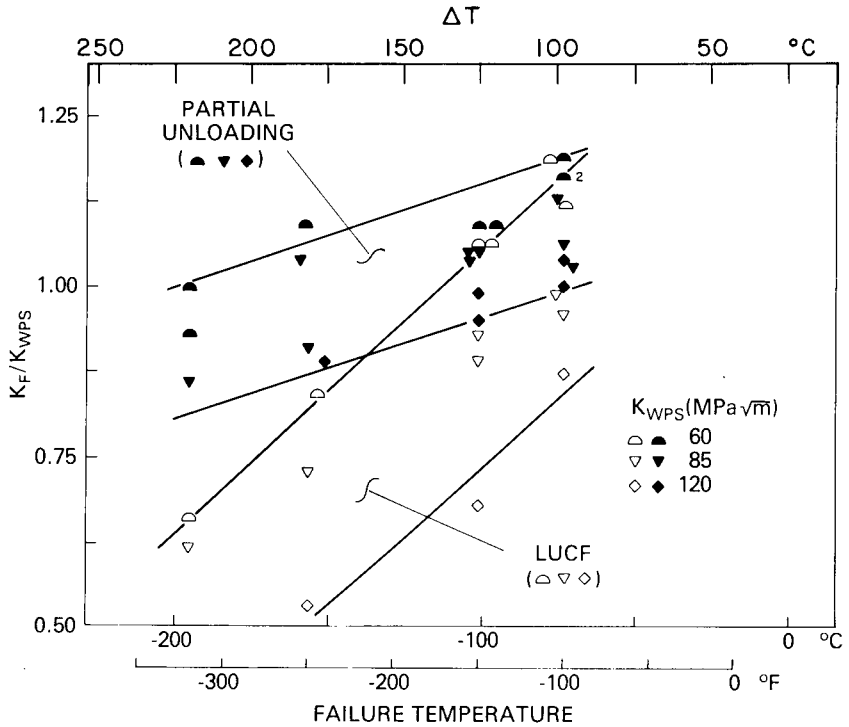

Fig. 7 — Results of WPS experiments from a previous study by the authors [1] showing the relationship of the failure level (K_F) to ΔT, to K_{WPS}, and to the degree of unloading (partial vs LUCF, where LUCF refers to load, unload, cool, fracture)

different from that exhibited by specimens loaded to an E-399 allowable value of K_{WPS} (for the same ΔT and failure path). Therefore it can be inferred that the overloaded specimens in the present study also reflect the behavior that would have been observed from tests of 150-mm-thick specimens. This trend is expected to continue to still higher K levels, but the existing data base is insufficient to verify this expectation.

In addition it was observed that the results of Fig. 6 exhibit no definite trend as a function of the ΔT value. This is contrary to the observation made in the preceding study (Fig. 7) wherein the effective elevation in K_{Ic}, due to WPS, diminished with increasing ΔT. With the present investigation, the variation in ΔT is only 28°C (50°F) compared with a ΔT range of 220°C (400°F) in the previous study. It is concluded that the range of ΔT associated with the present tests is too small to distinguish variations due to this variable in the effective K_{Ic}. Finally no trend could be attributed to the degree of unloading from the K_{WPS} level (25% vs 50% unloading). This result is also consistent with the previous study. In that investigation a trend in the fracture levels was observed only between a partial unloading of 30% and 60% with decreasing temperature and a complete unloading at the WPS temperature.

UNCLASSIFIED

DISCUSSION

In Ref. 1 (Fig. 7) it was shown that for a ΔT of 100°C and partial unloading the failure level always exceeded the K_{WPS} level, for the range of K_{WPS} investigated. Also, the elevation in resistance to crack initiation (K_{Ic}) due to WPS was shown to increase with a decrease in ΔT. The present study has investigated much smaller values of ΔT (33°C for the majority of the specimens) as would be expected during a LOCA. The use of this smaller ΔT also produced failures which consistently exceeded K_{WPS}. However the margin by which K_{WPS} was exceeded is essentially the same for a ΔT value of 33°C as it was for a value of 100°C. This fact implies that the effect of ΔT has saturated and that no further elevation in the ratio of K_F/K_{WPS} is to be expected as a function of decreasing ΔT.

The preceding conclusion can be rationalized on the basis of the yield-strength elevation associated with ΔT. In the previous study a model for the WPS behavior was described from which it was concluded that the yield-stress elevation with a large ΔT was responsible for the decreased benefit of WPS in terms of elevation in resistance to crack initiation. Thus the change in yield stress between the temperatures of T_F and T_{WPS} may be a more appropriate parameter than ΔT to characterize the WPS benefit. Since the yield stress changes very little over the present range of ΔT values, a trend in the WPS results was neither expected nor observed. The yield-strength increase associated with a larger value of ΔT (100°C) in the previous study is not much different from that associated with a ΔT of 30°C in the present investigation. This fact could explain the similarity in the K_F/K_{WPS} ratio for tests of these two ΔT values. The correspondence results because the ΔT in both studies was imposed over an absolute temperature range in which the yield stress does not exhibit a marked change with temperature.

Also, from the trend of Fig. 7, one would expect at least as great a value of K_F/K_{WPS} with a ΔT of 30°C as with a ΔT of 100°C, all things being equal. Thus, if the proposed WPS dependence on yield-strength change is correct, one can conclude from the previous study (Fig. 7) that the fracture levels illustrated in Fig. 6 are in fact the result of the WPS phenomenon and are not specifically due to an inherently high K_{Ic} of the particular specimen. This conclusion has been substantiated by statistical analyses, Appendix B.

With respect to vessel integrity, a major benefit of WPS during a LOCA is to prevent fracture as the K_I level decreases and eventually exceeds the K_{Ic} level. The decrease in K_I with time results from the cooling of the crack-tip region by the ECCS water. During the cooling of the vessel wall, however, the possibility exists for perturbations in the monotonic decrease of K_I with time due to temperature fluctuations in the circulating water. These fluctuations may cause a momentary rise in K_I and slightly reverse the trend of decreasing K_I with time. If this happens, one must reconsider the preceding conclusion wherein it was determined unlikely for crack initiation to occur with decreasing strain at the crack tip. Although these fluctuations may occur, the present results have shown that they can be of significance *only* if the level of warm prestress were to be exceeded after the K_I level falls below K_{Ic}. This possibility is considered to be remote. Therefore such perturbations are not believed to be of sufficient importance to detract from the benefits of WPS to vessel integrity previous defined.

RELATED RESEARCH TOPICS

Collectively the present study and the preceding investigation [1] have defined a means for projection of vessel integrity during a LOCA-ECCS based upon the WPS phenomenon. As discussed below, these studies have not addressed all possible variations in the significant parameters affecting crack extension. Several of these areas could form the basis for follow-on research studies, but none is believed to warrant serious concern for the vessel integrity during a LOCA. These areas are discussed to place in perspective the phenomenon of WPS and to alert the user to the potential uncertainties in its application.

K_{WPS} Level

To prevent formation of an excessively large crack-tip plastic zone during WPS, the experimental K_{WPS} levels were limited to a magnitude that was not larger than the measurement capacity of the specimen by E-399 rules (88 MPa$\sqrt{m}$, for a 76-mm-thick specimen). As illustrated in Fig. 2, it is theoretically possible for the K_I levels during a LOCA to exceed the preceding level by a considerable margin. It can be inferred from Ref. 1, as well as from the present study, that similar benefits of WPS will be obtained for higher K_{WPS} levels, up to 124 MPa$\sqrt{m}$. Nevertheless further studies with larger specimens would be required for a conclusive demonstration of the effective K_{Ic} elevation associated with peak K_{WPS} levels illustrated in Fig. 2 (such as 220 MPa$\sqrt{m}$).

Irradiated K_{Ic} and K_{IR} Curves

The interpretations of WPS to crack extension during a LOCA have been based on calculations for the RCM [2]. This model was intended to represent a worst-case condition in terms of a steel that is highly sensitive to radiation coupled with a neutron fluence that represents the end of life. Furthermore an analysis of crack extension in the RCM was based on the assumption of crack arrest when the K_I level dropped to the value of the K_{IR} curve defined in Section III of the ASME Code. Of course in the analysis the K_{IR} curve was elevated in temperature according to Regulatory Guide 1.99 [5] to account for the effect of irradiation. This temperature elevation assumes that the shape of the K_{IR} curve is unaltered by irradiation. However it has been shown [6] that irradiation can cause a marked decrease in the steeply rising shape of the Charpy-V curve. If this behavior is also reflected in the shape of the irradiated K_{IR} curve, then a reanalysis of the LOCA crack extension, accounting for WPS, will predict a greater degree of crack extension in the vessel wall than has been projected thus far. Current NRC-sponsored research is investigating the behavior of the irradiated K_{IR} curve.

Also, the irradiated K_{Ic} curve was obtained by translating the unirradiated K_{Ic} curve by a temperature increment defined in Regulatory Guide 1.99 [5]. Although the resultant K_{Ic} curve may be essentially correct, the temperature translation referred to in the Regulatory Guide pertains strictly to the K_{IR} curve. Application of this procedure to the K_{Ic} curve implies that the temperature elevation of the irradiated K_{Ic} and K_{IR} curves is identical.

UNCLASSIFIED

Low-Shelf Steel

Several of the U.S. commercial reactor vessels are expected to exhibit a low upper-shelf toughness of the beltline weld region after some years of service. The K_{Ic} levels of some of these irradiated welds are projected to be less than 165 MPa$\sqrt{m}$ (150 ksi$\sqrt{in.}$). If the K_I levels during a LOCA exceed the preceding value during warm prestress, a limited amount of stable (rising-load) crack extension will occur. While this extension need not be significant, the phenomenon should be characterized and interpreted to more accurately predict the crack extension during a LOCA.

SUMMARY AND CONCLUSIONS

This program has been an extension of previous research on WPS by the authors [1]. In the previous research a wide range of parameters was investigated, and in some cases more severe conditions were imposed than those projected for the LOCA-ECCS. In addition the preceding study did not address the case of a small ΔT. Since the latter is characteristic of the projected behavior during a LOCA, the present study was undertaken to demonstrate the phenomenon of WPS in terms of a small ΔT and to develop a correspondence with the results of the preceding program.

Investigation of a small ΔT presents certain difficulties in data interpretation. Because of the finite width of the K_{Ic} scatterband, coupled with a K_{WPS} level that must be imposed at a temperature above the K_{Ic} lower boundary, the failure levels also must lie within the K_{Ic} scatterband. Consequently an uncertainty exists as to whether the specimen fracture level is in fact a consequence of the WPS or whether it is simply the result of K_{Ic} scatter. To address this question, the program included the testing of many specimens at a single temperature to permit statistical analyses.

The results of the study are consistent with the trends evolved previously and therefore permit an optimistic assessment concerning vessel integrity during a LOCA. The major observations concerning the specimen behavior are that failure did not occur during the simultaneous unloading and cooling following WPS even though the critical K_{Ic} of the virgin material was attained and that without exception the failure level exceeded the level of WPS.

A statistical analysis of the specimen fractures within the K_{Ic} scatterband has demonstrated that WPS produces an increased resistance to crack initiation. For the case of a small ΔT it is concluded that although WPS may not elevate the toughness of a material whose K_{Ic} would be greater than K_{WPS}, it will produce an effective K_{Ic} elevation in material of lower toughness, so that a value less than K_{WPS} will not be observed.

The previous study suggested that the effective increase in K_{Ic} due to WPS would improve with decreasing ΔT. The present study with a small ΔT suggests that this effect has saturated and that a further elevation in K_{Ic} will not occur. The authors have suggested that the effective elevation in K_{Ic} is related to the change in yield strength that occurs over the ΔT increment. Thus the change in yield strength may be a more significant parameter than ΔT to characterize the benefit of WPS.

With respect to crack extension during a LOCA it was concluded that this event is precluded during the period of decreasing stress intensity with time following the WPS, since this behavior removes a necessary condition for fracture initiation. However minor temperature fluctuations in the ECCS water also will occur. This variation could result in a momentary reversal in the monotonic decrease in K_I at the crack tip. Fortunately the present studies have demonstrated that minor perturbations in an overall decreasing K_I trend are not significant, in that fracture is prevented unless the WPS level is exceeded.

Collectively the two studies have provided a means for projecting vessel integrity during a LOCA-ECCS based on the WPS phenomenon. Although certain areas may require additional study to fully characterize vessel performance for all material conditions, it is concluded that WPS can provide a positive mechanism to limit crack extension during a thermal shock. In terms of a reference calculational model of the vessel, under assumed worst-case conditions, it was concluded earlier that although WPS cannot prevent the initiation of shallow flaws, this phenomenon will limit crack penetration to a depth of 1/3 the vessel wall. The present study fully supports this assessment.

ACKNOWLEDGMENTS

The authors express their appreciation to the U.S. Nuclear Regulatory Commission, Division of Reactor Safety Research, for their support of this research. The authors are further indebted to W. E. Vesely for the preparation of Appendix B. Special thanks are extended to E. K. Lynn and G. R. Irwin for helpful discussions during this investigation.

REFERENCES

1. F.J. Loss, R. A. Gray, Jr., and J.R. Hawthorne, "Significance of Warm Prestress to Crack Initiation During Thermal Shock," NRL Report 8165, Sept. 1977; also Proc. 4th Intn. Conf. on Structural Mechanics in Reactor Technology, San Francisco, 15-19 Aug. 1977.
2. R.D. Cheverton, "Pressure Vessel Fracture Studies Pertaining to a PWR LOCA-ECCS Thermal Shock: Experiments TSE-1 and TSE-2," ORNL/NUREG/TM-31, Oak Ridge National Laboratory, Sept. 1976.
3. R.D. Cheverton, S.E. Bolt, and S.K. Iskander, "Thermal Shock Studies Associated with Injection of Emergency Core Coolant in Pressurized Water Reactors," Proc. 4th Intn. Conf. on Structural Mechanics in Reactor Technology, San Francisco, 15-19 Aug. 1977.
4. W.E. Vesely, memorandum to E.K. Lynn, U.S. Nuclear Regulatory Commission, 1977.
5. "Effects of Residual Elements on Predicted Radiation Damage to Reactor Vessel Materials," Regulatory Guide 1.99, U.S. Nuclear Regulatory Commission, Office of Standards Development, Washington, D.C., Apr. 1977.
6. F. J. Loss, editor, "Structural Integrity of Water Reactor Pressure Boundary Components, Progress Report Ending 31 May 1976," NRL Memorandum Report 3353, Sept. 1976.

UNCLASSIFIED

Low-Shelf Steel

Several of the U.S. commercial reactor vessels are expected to exhibit a low upper-shelf toughness of the beltline weld region after some years of service. The K_{Ic} levels of some of these irradiated welds are projected to be less than 165 MPa$\sqrt{m}$ (150 ksi$\sqrt{in.}$). If the K_I levels during a LOCA exceed the preceding value during warm prestress, a limited amount of stable (rising-load) crack extension will occur. While this extension need not be significant, the phenomenon should be characterized and interpreted to more accurately predict the crack extension during a LOCA.

SUMMARY AND CONCLUSIONS

This program has been an extension of previous research on WPS by the authors [1]. In the previous research a wide range of parameters was investigated, and in some cases more severe conditions were imposed than those projected for the LOCA-ECCS. In addition the preceding study did not address the case of a small ΔT. Since the latter is characteristic of the projected behavior during a LOCA, the present study was undertaken to demonstrate the phenomenon of WPS in terms of a small ΔT and to develop a correspondence with the results of the preceding program.

Investigation of a small ΔT presents certain difficulties in data interpretation. Because of the finite width of the K_{Ic} scatterband, coupled with a K_{WPS} level that must be imposed at a temperature above the K_{Ic} lower boundary, the failure levels also must lie within the K_{Ic} scatterband. Consequently an uncertainty exists as to whether the specimen fracture level is in fact a consequence of the WPS or whether it is simply the result of K_{Ic} scatter. To address this question, the program included the testing of many specimens at a single temperature to permit statistical analyses.

The results of the study are consistent with the trends evolved previously and therefore permit an optimistic assessment concerning vessel integrity during a LOCA. The major observations concerning the specimen behavior are that failure did not occur during the simultaneous unloading and cooling following WPS even though the critical K_{Ic} of the virgin material was attained and that without exception the failure level exceeded the level of WPS.

A statistical analysis of the specimen fractures within the K_{Ic} scatterband has demonstrated that WPS produces an increased resistance to crack initiation. For the case of a small ΔT it is concluded that although WPS may not elevate the toughness of a material whose K_{Ic} would be greater than K_{WPS}, it will produce an effective K_{Ic} elevation in material of lower toughness, so that a value less than K_{WPS} will not be observed.

The previous study suggested that the effective increase in K_{Ic} due to WPS would improve with decreasing ΔT. The present study with a small ΔT suggests that this effect has saturated and that a further elevation in K_{Ic} will not occur. The authors have suggested that the effective elevation in K_{Ic} is related to the change in yield strength that occurs over the ΔT increment. Thus the change in yield strength may be a more significant parameter than ΔT to characterize the benefit of WPS.

With respect to crack extension during a LOCA it was concluded that this event is precluded during the period of decreasing stress intensity with time following the WPS, since this behavior removes a necessary condition for fracture initiation. However minor temperature fluctuations in the ECCS water also will occur. This variation could result in a momentary reversal in the monotonic decrease in K_I at the crack tip. Fortunately the present studies have demonstrated that minor perturbations in an overall decreasing K_I trend are not significant, in that fracture is prevented unless the WPS level is exceeded.

Collectively the two studies have provided a means for projecting vessel integrity during a LOCA-ECCS based on the WPS phenomenon. Although certain areas may require additional study to fully characterize vessel performance for all material conditions, it is concluded that WPS can provide a positive mechanism to limit crack extension during a thermal shock. In terms of a reference calculational model of the vessel, under assumed worst-case conditions, it was concluded earlier that although WPS cannot prevent the initiation of shallow flaws, this phenomenon will limit crack penetration to a depth of 1/3 the vessel wall. The present study fully supports this assessment.

ACKNOWLEDGMENTS

The authors express their appreciation to the U.S. Nuclear Regulatory Commission, Division of Reactor Safety Research, for their support of this research. The authors are further indebted to W. E. Vesely for the preparation of Appendix B. Special thanks are extended to E. K. Lynn and G. R. Irwin for helpful discussions during this investigation.

REFERENCES

1. F.J. Loss, R. A. Gray, Jr., and J.R. Hawthorne, "Significance of Warm Prestress to Crack Initiation During Thermal Shock," NRL Report 8165, Sept. 1977; also Proc. 4th Intn. Conf. on Structural Mechanics in Reactor Technology, San Francisco, 15-19 Aug. 1977.
2. R.D. Cheverton, "Pressure Vessel Fracture Studies Pertaining to a PWR LOCA-ECCS Thermal Shock: Experiments TSE-1 and TSE-2," ORNL/NUREG/TM-31, Oak Ridge National Laboratory, Sept. 1976.
3. R.D. Cheverton, S.E. Bolt, and S.K. Iskander, "Thermal Shock Studies Associated with Injection of Emergency Core Coolant in Pressurized Water Reactors," Proc. 4th Intn. Conf. on Structural Mechanics in Reactor Technology, San Francisco, 15-19 Aug. 1977.
4. W.E. Vesely, memorandum to E.K. Lynn, U.S. Nuclear Regulatory Commission, 1977.
5. "Effects of Residual Elements on Predicted Radiation Damage to Reactor Vessel Materials," Regulatory Guide 1.99, U.S. Nuclear Regulatory Commission, Office of Standards Development, Washington, D.C., Apr. 1977.
6. F. J. Loss, editor, "Structural Integrity of Water Reactor Pressure Boundary Components, Progress Report Ending 31 May 1976," NRL Memorandum Report 3353, Sept. 1976.

UNCLASSIFIED

Appendix A

DOCUMENTATION FOR THE A533-B CLASS 1 STEEL PLATE FOR THE WARM-PRESTRESS TEST PROGRAM

Procurement specifications for the A533-B steel plate used in the WPS test program are summarized in Table A1. The chemical composition of the plate is given in Table A2. Procurement specifications were designed to secure material representative of current construction of reactor pressure vessels and were patterned after those evolved by Chicago Bridge and Iron (CB&I) Company. The specifications differ slightly in heat treatment condition in that the specifications were changed at the request of Lukens Steel to reflect their current practice.

Actual heat treatment conditions are identified in Table A3. Plate austenitizing, quenching, and tempering operations were conducted by Lukens; the long-term heat treatment for stress-relief annealing was conducted by NRL. This procedure included stress-relief annealing using a recirculating air furnace after the primary sectioning of the plate by flame cutting. During this anneal, work-piece temperatures were monitored continuously by means of mechanically attached thermocouples.

The mechanical property data for the plate (quarter-thickness location) listed in the mill test report are given in Table A4. Both the drop-weight nil-ductility-transition (NDT) temperature and the reference nil-ductility-transition temperature (RT_{NDT}). were -40°C (-40°F). The plate was certified by Lukens as A533-B Class 1 steel. However the mechanical properties listed in Table A4 show that this plate could also be classified as Class 2. In making comparisons with NRL-developed data, it should be recognized that the mill test samples were secured from test dropouts taken after the plate was tempered but before the primary stress relief anneal. Accordingly these samples were stress relieved separately from the main plate.

Tensile property data developed by NRL following the long-term stress-relief anneal are given in Table A5 and illustrated in Fig. A1. Strength values appear to be somewhat higher than those given by the mill test report (Table A4). Dynamic tear test data for the plate thickness region of interest (1/4 to 3/4 thickness) are reported in Table A6 and Fig. A2. Important to the evaluation and analysis of WPS results, good correspondence in DT properties in the transition temperature regime is shown for all three test locations. At DT upper shelf temperatures, a large difference in notch toughness is noted between quarter and midthickness positions and is believed due to impurity concentrations at the midthickness based on specimen fracture appearances. Good uniformity in upper shelf toughness however is not important to WPS specimen intercomparisons. Finally, the predicted NDT based on the DT curve (toe region) is in close agreement with the NDT measured with plate dropout tests (-40°C).

Table A1 — Summary of the Procurement Specifications for the A533-B Steel Test Plates

Specification	Requirements
ASTM type/grade	A533-B Class 1* (pressure vessel quality)
Gage	210 mm (8-1/4)
Pattern size (total)	2.6 by 4.5 m (104 in. by 175 in.) (RD)†‡
Melt furnace	Electric
Melt treatment	VIP (vacuum improved, PV quality)
Melt/slab number	A5401/2
Ingot the plate crossrolling	Standard (3:1) crossroll
Heat treatment	Austenitize 885-913°C (1625-1675°F); hold 1/2 hr per in. minimum; water quench. Temper 649-704°C (1200-1300°F); hold 1/2 hr per in. minimum; water quench. (The actual temper temperature and time used will be reported.) Stress relief tests only at 621^{+14}_{-28}°C (1150^{+25}_{-50}°F) for 40 hr.
Testing	Tensile tests are required to confirm that the A533 Grade B Class 1 plate is of PV quality. Drop-weight nil-ductility-transition temperature tests and Charpy V-notch impact tests will be performed to determine the actual RT_{NDT} for the quarter-plate-thickness location. Ultrasonic testing (ASME SA-578, Level 1, 100% search) to show that the plate is sonically sound is required.
Required properties	RT-NDT temperature shall not exceed +4°C (40°F).
Marking	Patterns shall be marked to show the primary rolling direction on orientation and position relative to prime plate and original ingot.

*ASTM Designation A533-B, Class 1, Book of ASTM Standards, 1972, Part 4, p. 617.
†RD = primary rolling direction.
‡The short dimension must be 20 cm from any as-heat-treated edge.

Table A2 — Chemical Composition (wt-%) of the A533-B Steel Plate (Mill Test Report Values)

C	Mn	Sn	P	S	Ni	Mo
0.23	1.40	0.25	0.005	0.004	0.70	0.57

UNCLASSIFIED

Table A3 — Heat Treatment of the A533-B Steel Plate
(210 mm (8.25 in.) thick)

Site	Heat Treatment
Lukens*	Austenitized 885-913°C (1625-1675°F), held 1/2 hr per in. minimum; water quenched; tempered 600°C (1220°F), held 1/2 hr per in. minimum, and water quenched; stress relieved 522-580°C (1025-1075°F), held 1/2 hr per in. minimum, and air cooled
NRL	Stress relief annealed 612°C +14°C -28°C (1150°F +25°F -50°F) for 32 hr and furnace cooled to below 316°C (600°F) at 56°C (100°F) maximum per hr

*Tests were stress relief annealed 593-635°C (1100-1175°F), held 40 hr, and furnace cooled to below 316°C (600°F).

Table A4 — Mechanical Properties of the A533-B Plate Given by the Mill Test Report. The report is for Plate A533-B1, Melt No. A5401, and orientation T (transverse (TL)) and is based on test specimens stress relieved by heating to 593-635°C (1100-1175°F), held 40 hr, and furnace cooled to below 316°C (600°F).

Yield Strength		Tensile Strength		Elong. in 2.0 in. (%)	RT_{NDT}		C_v Properties at 10°C (50°F)				
							Energy		Pct Shear	Lateral Expansion	
MPa	ksi	MPa	ksi		°C	°F	J	ft-lb		mm	mils
500	72.6	641	93.0	22	-40	-10	76	56	60	1.30	51
496	71.6	640	92.9	24			84	62	60	1.40	55
							87	64	60	1.47	58

Table A5 — Tensile Properties (Transverse (TL) orientation) of the A533-B Plate After the NRL Stress-Relief Anneal

Temperature		Stress at Different Plate-Thickness Locations											
		1/4 Thickness				1/2 Thickness				3/4 Thickness			
		0.2% Yield		Tensile		0.2% Yield		Tensile		0.2% Yield		Tensile	
°C	F	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
24	75	523	75.9	663	96.1	513	74.4	669	97.0	530	76.9	673	97.6
						524	76.0	682	98.9				
						525	76.2	682	98.9				
-18	0	541	78.1	690	100.1	523	76.2	692	100.1	545	79.1	701	101.6
-45	-50	556	80.7	715	103.7	546	79.2	724	105.0	568	82.4	728	105.6
		558	80.9	716	103.9					572	83.0	729	105.8
-68	-90	—		746	108.3					592	85.8	755	109.5
-90	-130	606	87.9	768	111.4	596	86.4	775	112.4	610	88.4	774	112.3

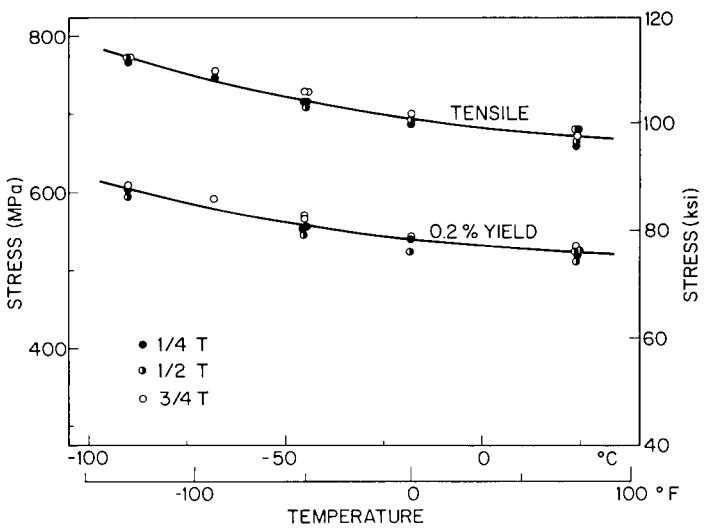

Fig. A1 — Yield and tensile test values for the A533-B1 test material

UNCLASSIFIED

Table A6 — Dynamic Tear Test Results for the A533-B Steel Plate (specimens 16 mm, 0.625 in., thick)

Temperature		DT Energy Absorption					
		1/4 Thickness		1/2 Thickness		3/4 Thickness	
°C	°F	J	ft-lb	J	ft-lb	J	ft-lb
-10	-40	141	101	84	62		
-18	0	171	126	155	114	165	122
-7	20	---			---	222	161
4	40	327	211	285	210		
16	60	372	271		---	321	237
27	80	464	312	450	332	576	125
38	100	709	523	591	136	743	518
49	120	1072	791	742	517	998	736
60	110	1523	1123	805	591	1383	1020
71	160	--		842	622	1517	1119
116	210	1565	1154	973	718	1461	1080

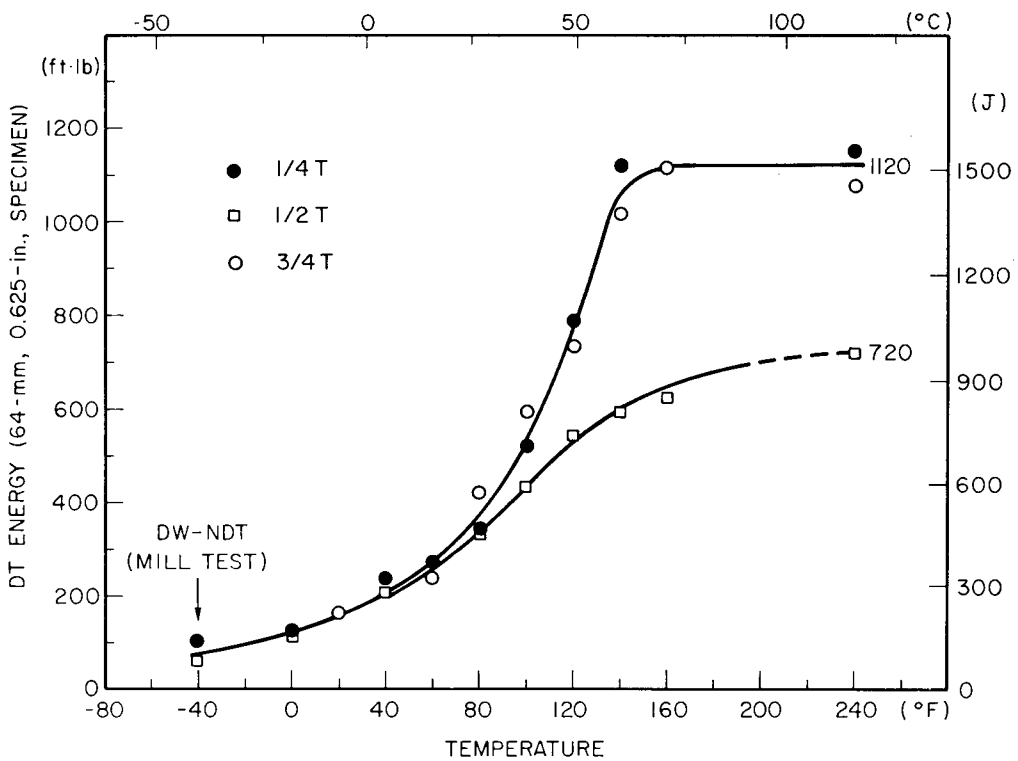

Fig. A2 — Dynamic tear test trends for the A533-B1 plate used in the test program

Appendix B

STATISTICAL ANALYSES OF WPS EFFECTS

One set of data in Fig. 6 consists of ten WPS specimens which all failed at K_{Ic} values higher than the median value with no WPS. (The median value is 88 MPa$\sqrt{m}$ and the temperature is -46°C.)

For a hypothesis test assume as the null hypothesis (H_0) that WPS has no effect on K_{Ic}. The alternative hypothesis (H_1) is that WPS increases K_{Ic}:

H_0: WPS has no effect;

H_1: WPS increases K_{Ic}.

If we reject H_0 based on the data, then we have confidence that WPS does increase K_{Ic}.

For the actual statistical test the binomial distribution is employed. If the ten specimens are assumed independent and essentially identical, under the null hypothesis the probability that a measured K_{Ic} exceeds the median value with no WPS is 0.5. The probability that all ten specimens have measured values exceeding the median is $0.5^{10} = 0.000977 \approx 0.001$. The observed significance level is thus approximately 0.1%, and the confidence we have in rejecting H_0 is approximately 99.9%. (In a statistical sense, the term "confidence" means here that if WPS had no effect, then 99.9% of the time we would see *fewer than ten samples exceeding the median.*) Since the observed significance level is so small (0.1%), moderate deviations from the binomial assumptions, including uncertainty in the median, should not significantly affect the conclusion. Hence H_0 is rejected, and we have substantial confidence that WPS effectively increases K_{Ic}.

The binomial distribution can also be used to obtain a bound on the amount WPS increases K_{Ic}. Let p be the probability that a measured K_{Ic} (under WPS) exceeds the median value of K_{Ic} with no WPS. From binomial tables, with ten specimens and ten observed successes, the 95% lower confidence bound on p is 0.69. Thus with 95% confidence, even including measurement uncertainties, there is at least a 69% probability that a measured K_{Ic} under WPS will exceed that median K_{Ic} under no WPS. With use of a sampling distribution the 69% probability could be translated to an estimated increase in the median value of K_{Ic}.