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ULTRASONIC VELOCITIES
AND CRITICAL-ANGLE-METHOD CHANGES
IN IRRADIATED A302-B AND A542-B STEELS

April 1969

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DEVELOPMENT REPORT

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ULTRASONIC VELOCITIES AND CRITICAL-ANGLE-METHOD
CHANGES IN IRRADIATED A302-B AND A542-B STEELS

By

D. O. Hunter

NDT Methods Development Section
Nondestructive Testing Department
Systems and Electronics Division

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ABSTRACT

Ultrasonic critical-angle-method amplitude changes and ultrasonic shear and longitudinal velocity changes are measured on reactor irradiated A302-B and A542-B low alloy steels.

For specimens irradiated at temperatures between 140 and 350 °F, shear velocity decreased from about 0.2% at 1.5×10^{18} nvt to 0.6% at 1 to 2×10^{20} nvt. Longitudinal velocity decreased from 0.1% to 0.3% at similar fluences. Measurements of velocities changes for specimens irradiated at temperatures between 610 and 680 °F were inconclusive due to the small changes. There were indications, however, that high temperature irradiated specimens had experienced increased velocities before decreasing velocities trends were established. Critical angle amplitude changes are generally comparable to velocities changes.

Anomalies in velocities and critical angle curves are thought to be primarily as a result of scatter in unirradiated material and irradiation temperature variations among test specimens. Neutron energy-spectrum variations also could feasibly have contributed to anomalies.

Possible radiation damage and recovery mechanisms are discussed along with their possible effects on elastic constants.

Measurements methods and apparatus are described.

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ULTRASONIC VELOCITIES AND CRITICAL-ANGLE-METHOD
CHANGES IN IRRADIATED A302-B AND A542-B STEELS

D. O. Hunter

INTRODUCTION

This report describes results of a study to determine feasibility of some ultrasonic methods for detecting and measuring radiation damage in low alloy steels. The nature of the radiation damage and its effects on mechanical properties is not determined during the study; consequently, correlation is made to neutron fluence with temperature as a parameter.

Ultrasonic methods and equipment used are described. Some discussion of possible radiation damage and recovery mechanisms and their effects on elastic properties are included.

SUMMARY

One of the consequences of radiation damage to low alloy steels is impact embrittlement, one measure of which is the amount of upward shift in nil-ductility transition temperature. Radiation embrittlement impairs the ability of a structure, under stress, to arrest the propagation of a crack and thus degrades the safety factor of a reactor pressure vessel.

The cause(s) and prevention of embrittlement have been and still are under study. Simultaneously, some efforts are being made to develop methods of detecting and measuring embrittlement thus contributing to incipient failure diagnosis. Ultrasonic methods, which are adaptable to both laboratory and field applications, are known to be sensitive to the small, subtle microstructural changes similar to those which characterize radiation damage. Accordingly, some ultrasonic measurements were made on irradiated

steels to determine the feasibility of ultrasonic methods for detecting and measuring radiation damage.

Three measurement methods were used to determine: 1) changes in shear velocity, $\Delta V_S/V_S$, 2) changes in longitudinal velocity, $\Delta V_L/V_L$, and 3) changes in critical angle signal amplitude, ΔA_{CA} . In addition, dimensional changes, changes in density, and approximate materials scatter and measurement-errors were determined. From velocity and density changes, apparent changes in some elastic constants are calculated. Some possible radiation damage and recovery mechanisms and their qualitative effect on elastic constants and propagation velocities are discussed. Experimental procedure, measurement methods and apparatus, and facilities are described.

Results may be summarized as follows for specimens irradiated at temperatures between about 140 and 350 °F:

- . Shear velocity decreased as a function of neutron fluence >1 MeV from about 0.2-0.3% at about 1.5×10^{18} nvt to about 0.6-0.7% at about 1 to 2×10^{20} nvt.
- . Longitudinal velocity decreased from about 0.1-0.2% to 0.3-0.4% at similar fluences.
- . Critical angle signal amplitude changed approximately in proportion to the velocity changes.
- . Most specimens experienced some swelling resulting in indicated density decreases typically in the range of 0.1-0.25%.
- . The velocity and density changes suggest changes in elastic constants approximately as follows: a) decrease in shear modulus, $\Delta G/G$, 0.6 to 1.3%, b) decrease in bulk modulus, $\Delta K/K$, 0.06 to 0.48%, c) decrease in Young's modulus, $\Delta E/E$, 0.5 to 1.2%, and d) increase in Poission's ratio, $\Delta \nu/\nu$, 0.3 to 0.6%.

Results for specimens irradiated at temperatures between about 610 and 680 °F are inconclusive since measured changes were in the same order of magnitude as scatter and error. Indications are, however, that velocities have increased at fluences lower than used in this study but then subsequently decreased so that, at fluences reported herein, velocities are decreasing as exposure increases, but with some specimens still showing a net increase.

CONCLUSIONS

The ultrasonic methods described herein are capable of detecting a type of irradiation damage which remains relatively stable at irradiation temperatures less than about 350 °F. Other forms of irradiation damage still stable at irradiation temperatures between about 610 and 680 °F are not easily detected.

The surface-sensitive critical angle method appears to be the most sensitive of the three methods; but, in proposed field measurements of pressure vessels, has the disadvantage of being useful only for surface measurements. The velocity measurements methods, while sensitive to changes throughout the thickness of a vessel, have a disadvantage of measuring an unknown thickness. Measurements of both shear and longitudinal velocities at one spot would eliminate the thickness unknown while still allowing a measure of radiation damage since shear velocity changes are greater than longitudinal velocity changes.

Regardless of the method used, greatly improved measurement accuracies would result if pre-irradiation measurements were taken and if the measurements are taken on specially prepared surveillance specimens. It is

likely, in fact, that irradiation damage at high irradiation temperatures could be measured if pre-irradiation measurements were available.

The apparent sensitivity of velocity changes to irradiation temperature suggests laboratory usefulness of ultrasonic methods while studying recovery mechanisms in alloys as influenced by post-irradiation heat treatment; furthermore, there could be some additional information extracted from measurements of changes in velocity and attenuation when ultrasonic test frequency and static bias stresses are used as parameters.

The poor response of the ultrasonic methods to specimens irradiated at temperatures about 610-680 °F indicates that while there may be ultrasonic velocities changes to physical microstructural changes, the changes are not great enough to be related to mechanical properties changes expected at that temperature range.

Changes in velocity are in such a direction, for the low temperature irradiated specimens, as to have resulted from decreases in elastic moduli. The most likely cause of a net decrease in the apparent elastic moduli in irradiated materials is the presence of decreased atomic density zones such as voids, depleted zones, displacement spikes, vacancies and vacancy clusters, loops, bubbles, etc. The fact that velocities have not decreased nearly as much at high irradiation temperatures as at low irradiation temperatures is compatible with theories of simple recovery mechanisms related to increased defect mobility and hence improved annealing or recovery at higher temperatures.

OBJECTIVES

The objective of this study has been to determine the feasibility of the ultrasonic critical angle method for detecting irradiation induced embrittlement thus laying some groundwork for a subsequent engineering effort at developing a practical nondestructive test. In the process of investigating the ultrasonic critical angle method, velocity changes measurements were also made which established changes in ultrasonic wave propagation velocity as being a principal cause of observed changes in critical angle method signal response. Although it was impossible to make highly accurate measurements of velocity changes, the objectives were broadened to include a determination of approximate velocity changes.

Since the velocity changes can be related to changes in elastic moduli and since some radiation damage and recovery mechanisms can be postulated by the behavior of elastic moduli as influenced by irradiation temperature, post-irradiation annealing, etc., ultrasonic methods offer a means by which radiation damage may be studied in the laboratory. Such studies have in fact been made for many years but generally only on single crystals or polycrystalline elements. Through the media of frequency and strain dependent ultrasonic velocity and attenuation changes measurements, and by conducting measurements with post-irradiation annealing temperature as a parameter, ultrasonic methods appears able to make contributions to the study of radiation damage and recovery in polycrystalline metals and alloys. In support of this viewpoint, the objective of this study has been further enlarged to include a general discussion of certain aspects of radiation damage and its effects on elastic moduli.

STATEMENT OF PROBLEM

Nondestructive Assessment of Radiation Damage

There are a number of ways in which irradiation damage can affect mechanical properties of metals. Service environment plays an important role in determining which properties change and to what extent they change. Low alloy steels are known to become appreciably embrittled with noticeable effects showing up after about 1×10^{18} nvt >1 MeV. The serious nature of the embrittlement is reflected in the steels' inability to arrest the propagation of a crack provided a certain combination of temperature, stress, flaw size, and embrittlement are simultaneously present.⁽¹⁾ The crack arrest temperature (CAT) for low alloy steels is that temperature above which a propagating crack would be stopped by the steel itself through redistribution of stresses to areas surrounding the crack. At only 30-60 °F below the CAT lies the nil-ductility-transition temperature (NDTT), the temperature below which fracture stress equals yield strength. Thus, at temperatures below the NDTT, there would be no yielding before fracture stresses and rapid brittle fracture would occur. The narrowness of the temperature separation between crack arrest and crack propagation conditions is illustrated by the transition curves for A302-B shown in Figure 1 where fracture stresses have been correlated to Charpy V-notch fracture stresses. Depending on the alloy, service environment, and a host of known and suspected parameters, the transition temperature will gradually increase with increasing neutron exposure. Shifts in transition temperature as high as 545 °F have been observed.⁽²⁾

FIGURE 1
Effects of Irradiation and Temperature on Nil-Ductility-Transition Temperature
for A302-B

Naturally, those concerned with engineering and operation of nuclear power reactors are concerned that the critical combination of temperature, stress, crack size, and metal embrittlement might occur in pressure vessels resulting in a catastrophic accident. Consequently, substantial research effort has been devoted to determine the cause(s) and prevention of the transition temperature shift. Although much progress has been made, the problem still exists and undoubtedly will exist for many years, particularly as nuclear power generators become aged and their pressure vessels more embrittled.

Some measure of assurance to safe operating conditions could be provided by periodically taking measurements on the critical components using nondestructive methods or by making the conventional mechanical tests on surveillance specimens. Irradiation of surveillance specimens is planned or being done at many reactors in the United States.⁽³⁾ No nondestructive method has yet been developed although studies have been made in this direction.^(4,5) Some advantages of reliable nondestructive methods are:

- . A certain amount of error introduced by material scatter can be avoided in nondestructive measurements if measurements can be made before irradiation.
- . Frequent nondestructive tests can be made with no threat of depleting the supply of surveillance specimens.
- . Measurements could probably be made on the vessel itself rather than on test specimens.
- . Cost of conducting measurements should be significantly less than those of destructive methods.

Radiation Damage

It is generally agreed that radiation damage has as its basis the microstructural interactions which take place as a result of atomic displacements caused by collisions of neutrons with atoms and the subsequent chain-reaction collisions from the struck atom and the atoms it strikes, etc.⁽⁶⁾ If a metal was homogeneous on a microstructural scale before irradiation, in all likelihood it ceases to be homogeneous after irradiation unless completely annealed. Inhomogeneities exist as a result of the neutron bombardment, subsequent atomic displacements, and still subsequent behavior of the radiation defects.

Current theories of radiation damage to steel at reactor operating temperatures emphasize the formation and growth in size and numbers of regions characterized by reduced atomic density. Such regions are formed as a result of depleted zones⁽⁷⁾ where interstitials are channeled relatively far away from the depleted area, displacement spikes⁽⁸⁾ where interstitials concentrations on the periphery of a multiple vacancy have annealed, and clustering or growth of the reduced density zones. Free interstitials or high atomic density regions are thought to be fewer than the low density regions because of a lower activation energy (greater mobility at a given temperature).⁽⁹⁾ Many interstitials are thought to anneal out by recombination; migration to unsaturable sinks, e.g., grain boundaries, surfaces, etc., where their presence is largely unfelt; and formation of dislocations through collapse of clusters. Those interstitials which interact in some way with dislocations are thought to contribute to changes in mechanical properties.⁽¹⁰⁾ Some of the reduced density zones likewise affect mechanical properties through interaction with dislocations. Elevated temperatures apparently

enhance the annealing of interstitials and growth of vacancy clusters.⁽¹¹⁾ When temperatures reach about 750 °F in steel, vacancy clusters are thought to start to dissociate and ultimately anneal out as temperature is further increased.⁽¹²⁾

Hardening is thought to be a result of radiation defects, such as clusters of vacancies or interstitials, reacting with dislocations, either at their source or after some migration in such a manner as to restrict their motion.⁽¹³⁾ Embrittlement mechanisms apparently vary with different materials, but generally are thought to be related to hardening⁽¹⁴⁾ or similar mechanisms such as one involving carbon-vacancy-complex interaction with dislocations.^(15,16)

Increases in transition temperature is a complex function of many parameters such as composition, gas and residual content, pre-irradiation heat treatment, grain size, cold working, neutron flux energy spectrum and dosage temperature during irradiation, and post-irradiation heat treatment.^(17,18) Even size of the irradiated material is thought to be a factor.⁽¹²⁾

Temperature during irradiation is important for, among other things, in certain temperature ranges it contributes to self-annealing. Thus, when steel is irradiated at a self-annealing temperature, the magnitude of transition temperature shift may be much less than at other temperatures.^(2,17,19) For iron, there seems to be a break point in irradiation temperature which more or less defines that temperature above which tensile embrittlement is minimal⁽¹⁶⁾ within dosage limitations. A break point temperature for impact embrittlement is thought to be in the vicinity of 450-550 °F for many low alloy steels.⁽²⁾ Since most reactors will be operating well above

room temperature and probably in the vicinity of 550-650 °F, it was felt necessary to be able to distinguish between irradiation damage at low temperatures (below about 350 °F) and irradiation damage at high temperatures (above about 600 °F). For that reason, the experimental procedure in this study included two groups of specimens to cover the two temperature ranges. These two groups are identified in Appendix B and will, at times, be referred to as the high temperature group or low temperature group, respectively.

Effects of Radiation on Elastic Properties

Since an ultrasonic investigation into radiation damage must necessarily concern itself with changes to elastic properties, a literature search was made to determine what effects radiation has on elastic moduli and what other investigators have learned after conducting ultrasonic studies on irradiated material. A description of some of the mechanisms follows in this section; some quantitative examples are in Appendix F.

Interatomic Potentials Change due to Interstitials and Vacancies

Perhaps the pioneering work on theoretical effects was by Dienes^(20,21) who predicted an increase in elastic moduli due to the effects of interstitials and a decrease due to vacancies. The changes were calculated on the basis of atomic interaction potentials with relaxation effects taken into account. In the presence of equal numbers of both types of point defects, the net effect would be an increase in moduli. Regardless of the type of defect distribution, the net effect on elastic moduli was considered to be a direct bulk effect due to atomic readjustments around the point defects.

Interaction of Radiation Defects with Dislocations

Other effects on moduli occurs simultaneously with the effects predicted by Dienes and it has thus been difficult to experimentally separate the various effects. A number of investigations have met with some success, however, using both high^(22,23) and low⁽²⁴⁾ frequency ultrasonic measurements on specially prepared irradiated single crystals, or, in one case, low frequency measurements on irradiated polycrystalline tungsten.⁽²⁵⁾

The irradiation effect on elastic moduli which is most frequently studied deals with the interaction of defects with vibrating dislocations. It is not termed a direct effect but rather an indirect effect because a measured elastic modulus is composed of a pure part and an apparent part--the dislocation contribution. The effect of irradiation is to reduce the amount of dislocation contribution so that one approaches a measurement of the real elastic modulus (which, however, in the meantime may also be changed by increased irradiation dosage).

Detailed descriptions of the dislocation interaction mechanism are widely found in the literature.^(24,26,27) In essence, the mechanism comes about because migrating defects and dislocations interact in such a manner that the vibratory length of dislocation segments, under an alternating stress such as ultrasonic stress waves, are reduced thus affecting the stress-strain relationships as well as the energy losses (internal friction) involved in exciting the dislocations. Since the pinned dislocation segments vibrate with a shorter length than do the unpinned segments, they are found to be frequency dependent and, in fact, a resonance peak is predicted.^(22,28) If the excitation stresses are raised sufficiently high, enough energy is present to enable breakaway of the dislocation loops from their pinning

points with a consequent decrease in moduli and increase in friction losses.^(29,30) Thus, there is a second parameter affecting dislocations vibrations contribution to elastic moduli, a strain amplitude dependent component. A static stress is sometimes superimposed on the alternating stress in order to observe the strain dependent component since ultrasonic stress waves are generally low amplitude.⁽²⁹⁾

Dislocation density also affects the apparent elastic moduli and would be evidenced by a decrease in velocities as dislocation density increases. Dislocation density is seldom factored into experiments designed to test the dislocation damping theory, possibly because it appears more difficult to alter dislocation density than to alter length between pinning points. It has been shown, however, that neutron irradiation will increase dislocation density in A212-B (a low alloy steel used in reactor pressure vessels) from about $2 \times 10^8/\text{cm}^2$ to $3 \times 10^{10}/\text{cm}^2$ when irradiated at about 200 °F to an exposure of about $5 \text{ to } 8 \times 10^{19} \text{ nvt}$ >1 MeV.⁽³¹⁾ Irradiation caused dislocations are thought to grow as loops from collapsed interstitial or vacancy clusters and achieve a size of 1000-4000 Å before losing the loop character. The radiation caused dislocations can presumably be pinned by other radiation produced defects or interact with existing dislocations, thus reducing the increased dislocation density contribution to decreased elastic moduli. Although dislocation density is not thought to be directly responsible for changes in mechanical properties, the irradiation produced dislocations anneal out in about the same temperature range (600-800 °F) as that at which recovery of radiation-induced notch embrittlement occurs.⁽³¹⁾ It is noted, however, that dislocations present before irradiation do not anneal out as readily and a high dislocation density remains in A212-B even after 1 hour at 850 °F.⁽³¹⁾

Elasticity Changes due to Porosity (Reduced-Atomic-Density Zones)

A third possible contributor to changes in measured elastic moduli may be closely identified with the real moduli changes (contrasted to apparent changes) predicted by Dienes. Mackenzie, using classical elasticity relationships, has derived expressions relating changes in bulk and shear moduli to the change in density resulting from a material becoming full of small spherical holes.⁽³²⁾ Bradfield has re-expressed Mackenzie's equations into more convenient forms involving only Poisson's ratio and relative densities ratio. Both bulk and shear moduli are predicted to decrease with an increase in volume percentage of holes; the effect of holes size distribution is, within limits, expected to be minor. Bulk modulus is predicted to decrease more than shear modulus for the same change in density.

Scattering of Sound Waves by Radiation Defects

Truell, et al^(34, 35) also have studied effects of spherical holes, and spherical elastic media as well, on changes in ultrasonic wave velocities, which then can be related to changes in elastic moduli using the appropriate equations. Under conditions of the Rayleigh approximation for scattering (scatterer is very small compared to ultrasonic wavelength), and assuming radiation defects as being approximately spherical, a fractional velocity change becomes a function of the density of cavity scatterers and the elastic properties of the material. A similar expression relates velocity change to the properties of elastic scatterers and their host elastic media.

In single silicon crystals, Truell found that neutron irradiation caused a decrease in shear velocity⁽³⁶⁾ but an increase in compressional (longitudinal) velocity.⁽³⁵⁾ In conducting experiments on neutron irradiated silicon, Truell concluded observed velocity changes were caused by the

presence of scattering centers rather than dislocation pinning, since attenuation measurements failed to reveal the predicted attenuation changes based on dislocation pinning theory. The dislocation theory predicts a decrease in attenuation whereas the scattering theory predicts an increase in attenuation; both effects could be simultaneously present.

It has been observed, however, that the effect due to dislocation damping will quickly saturate⁽³⁷⁾ as a function of radiation exposure whereas the scattering center contribution presumably can continue to grow. Muss and Townsend⁽²⁵⁾ observed, in irradiated polycrystalline tungsten, that dislocation saturation occurred at $\sim 2 \times 10^{16}$ d/cm² but Young's modulus continued to change, a decrease, in a linear fashion up to 8×10^{16} d/cm², the experiment's exposure limit. They attribute the continued decrease to the bulk effect of vacancies since temperature during the experiment was ~ 300 °K, a temperature at which vacancies in tungsten are immobile but at which interstitials are mobile and thus annealed out.

Bradfield notes another possible contributor to apparent changes in elastic moduli.⁽³³⁾ As a stress wave propagates through a polycrystalline material it is continually experiencing mode transformations from longitudinal to shear, shear to longitudinal, etc., as it encounters interfaces between crystals. Thus, a longitudinal velocity in polycrystalline material could appear to be less than a longitudinal velocity in a pure crystal, regardless of which crystal axis is measured since a component of the wave in the polycrystalline material would have traveled at shear velocities. This concept could be extended to include other scatterers besides crystal interfaces. It is likely, however, that such scattering would be akin to the scattering

described by Truell⁽³⁶⁾ who regards "velocity changes arising from scattering as resulting from distortion or perturbation of the wave front as the wave passes through the change in the elastic medium offered by the scatterer".

Summary

Several mechanisms may contribute to changes in moduli:

- Dislocation pinning - for low amplitude ultrasonics will cause an apparent increase in moduli with increasing neutron dosage; should have a frequency sensitive component and a strain sensitive component.
- Dislocation density - will cause an apparent decrease in moduli with increasing neutron dosage (increasing dislocation density); most dislocations probably are pinned during irradiation soon after forming. Those that are not pinned would constitute a reduced contribution to the apparent moduli decrease.
- Lattice inhomogeneities - point defects, clusters of point defects, or other lattice disturbances cause a redistribution of lattice stresses with interstitials causing an increase and vacancies a decrease in moduli. The change caused by interstitials is greater than that by vacancies, but since interstitials anneal out more rapidly, it is likely that a net effect at reactor temperatures would be that from vacancies.
- Scattering - scattering centers, e.g., interstitial or vacancy clusters, cause distortion of propagating stress waves resulting in changes in velocities. Density and the elastic properties of the scattering centers relative to those of the host media determine whether velocities increase or decrease. In the special case of

spherical cavity scatterers, MacKenzie has predicted that both longitudinal and shear velocities (moduli) will decrease, whereas Truell predicts an increase in longitudinal velocity and suggests that experimental increases in V_L and decreases in V_S are caused by cavity scatterers.

Another scattering effect comes about because of mode changes in an inhomogeneous elastic material. Presumably, the effect is always a decrease in measured longitudinal velocity (and increase in measured shear velocity) but is not considered to be a real change since the apparent amount of change decreases with increased measurement accuracy.

RESULTS

Nomenclature

A description of the specimen's preparation is found in Appendix A. A description of nomenclature used when referring to material position in donor plate, temperature during irradiation, and comparative neutron fluence is found in Appendix B and further detailed in Tables II, III, and IV. An illustration of measurement positions on specimens and their nomenclature is found in Figure 26.

Scatter and Error

Scatter for all measurements, shear and longitudinal velocities, and critical angle signal amplitude, is defined as "the probable variation in the measured $\Delta V_S/V_S$, $\Delta V_L/V_L$, and ΔA_{CA} , respectively, as a result of the unknown elastic properties variations that existed in the specimens before irradiation". Error is defined as "a possible variation in the measured $\Delta V_S/V_S$, $\Delta V_L/V_L$, and ΔA_{CA} because of inaccurate measurements". A more

complete description of how scatter and error were determined may be found in Appendix E. Scatter and error in Figures 2 through 10 are shown as possible variances in the position of the unirradiated references.

Changes in Shear Velocity, $\Delta V_S/V_S$

Data tabulated in Tables VIII, IX, and X, Appendix E, are plotted in Figures 2, 3, and 4. From these data and curves the following observations are made:

- . Neutron irradiation has caused a decrease in shear velocity in the approximate amount of 0.20% per decade in the range of $\sim 10^{18}$ to 2×10^{20} nvt > 1 MeV for low temperature ($T \approx 140-350$ °F) reactor exposures. Ignoring anomalies, the relationship may be expressed as $\Delta V_S/V_S$ in % $\approx - \left(A_S + 0.2 \log \frac{\phi t}{10^{18}} \right)$ where $A_S \approx 0.2\%$ and ϕt = neutron fluence > 1 MeV.
- . Change in shear velocity appears to be in the decreasing direction for high temperature ($T \approx 610-680$ °F) reactor exposure; but the rate of change appears to be less, about half that of the low temperature specimens.
- . The positions of the high temperature curves suggest the possibility that shear velocity had initially increased at some dosage lower than used in this study. As exposure increases, the direction of change reverses and ultimately reaches a net decrease.
- . For low temperature exposures the amount of velocity change due to irradiation is distinguishable from that of unirradiated specimens, despite the estimated maximum scatter and error, at even the lowest exposures ($\sim 1.5 \times 10^{18}$ nvt).

FIGURE 2
Change in Ultrasonic Shear Velocity in Irradiated A302-B, from Top of Plate

FIGURE 3
Change in Ultrasonic Shear Velocity in Irradiated A302-B, from Middle of Plate

FIGURE 4
Change in Ultrasonic Shear Velocity in Irradiated A542-B

- Although not consistent, the velocity changes in the 1LM family (A302-B from the middle of the plate) are generally greater than for the 1LT family (A302-B from the top of the plate).
- A tendency towards saturation appears to start in the region $2 \text{ to } 5 \times 10^{19}$ nvt at low irradiation temperatures.

Changes in Longitudinal Velocity, $\Delta V_L/V_L$

Data tabulated in Tables XI, XII, and XIII, Appendix E, are plotted in Figures 5, 6, and 7. From these data and curves the following observations are made:

- Neutron irradiation has caused a decrease in longitudinal velocity in the approximate amount of 0.10% per decade in the range of $\sim 10^{18}$ to 2×10^{20} nvt > 1 MeV for low temperature ($T \approx 140\text{--}350$ °F) reactor exposures. Ignoring anomalies, the relationship may be expressed as $\Delta V_L/V_L \approx - \left(A_L + 0.1 \log \frac{\phi t}{10^{18}} \right)$ where $A_L \approx 0.10\%$ and ϕt = neutron fluence > 1 MeV.
- Longitudinal velocity appears to decrease for high temperature ($T \approx 610\text{--}680$ °F) reactor exposures; the rate of change appears to be less than that of low temperature exposures.
- The positions of the high temperature curves suggest the possibility that longitudinal velocity had initially increased at some low fluence, and then subsequently reversed direction at some higher fluence value still less than 2×10^{19} .
- Velocity changes in A302-B cut from the middle of a plate (1LM family) are generally greater than for A302-B from the surface of the plate (1LT family).

FIGURE 5
Change in Ultrasonic Longitudinal Velocity in Irradiated A302-B, From Top of Plate

FIGURE 6
Change in Ultrasonic Longitudinal Velocity in Irradiated A302-B, from Middle of Plate

FIGURE 7
Change in Ultrasonic Longitudinal Velocity in Irradiated A542-B

Changes in Elastic Properties

The effect of irradiation on apparent elastic properties has been calculated for three specimens, 1C1LT, 1C5LT, and 1H4LT, with sample calculations shown for 1C5LT in Appendix F. Calculations will be more accurate for 1C5LT than for 1C1LT or 1H4LT since changes in C5 are large enough that measurement errors and material scatter have a smaller effect. Measured changes for H4 are within experimental error and consequently the calculated changes in elastic constants must also be within experimental error.

The various elastic property changes for the three specimens are listed in Table I. A negative sign denotes a decrease and a positive sign denotes an increase in the property. From the calculated data in Table I, the following observations are made:

- . Direction of changes for specimens 1C1LT and 1C5LT are in agreement with each other; relative magnitude of changes are compatible with measured changes in velocities and density. Changes indicate an apparent more compliant structure.
- . Changes for specimen 1H4LT are too small to be meaningful.

Changes in Critical Angle Signal Amplitude, ΔA_{CA}

Data tabulated in Tables 14, 15, and 16, Appendix E, are plotted in Figures 8, 9, and 10.

From the critical angle data and curves the following observations are made:

- . Neutron irradiation has caused an increase in critical angle signal ΔA_{CA} in the approximate amount of $\Delta A_{CA}' + 15 \log \frac{\phi t}{10^{18}}$ in the

TABLE I
CHANGES IN APPARENT ELASTIC PROPERTIES FOR
THREE IRRADIATED A302-B SPECIMENS

	<u>Specimen Identification</u>		
	<u>1C1LT</u>	<u>1C5LT</u>	<u>1H4LT</u>
Change in Shear Velocity $\Delta V_S/V_S, \%$	-0.259	-0.538	+0.042
Change in Longitudinal Velocity $\Delta V_L/V_L, \%$	-0.102	-0.292	+0.037
Change in Density $\Delta \rho/\rho, \%$	-0.06	-0.21	-0.14
Change in Shear Modulus $\Delta G/G, \%$	-0.58	-1.286	-0.056
Change in Bulk Modulus $\Delta K/K, \%$	-0.06	-0.48	-0.07
Change in Young's Modulus $\Delta E/E, \%$	-0.50	-1.176	-0.059
Change in Poissons Ratio $\Delta \nu/\nu, \%$	+0.32	+0.60	-0.01
$V_S \approx 3.22 \times 10^5 \text{ cm/sec}$ $V_L \approx 5.94 \times 10^5 \text{ cm/sec}$ $\rho \approx 7.8 \text{ gm/cm}^3$ $G \approx 8.09 \times 10^{11} \text{ dynes/cm}^2$ $K \approx 16.71 \times 10^{11} \text{ dynes/cm}^2$ $E \approx 20.9 \times 10^{11} \text{ dynes/cm}^2$ $\nu \approx 0.291$	} for steel

FIGURE 8
Change in Ultrasonic Critical Angle Signal Amplitude for Irradiated A302-B, from
Top of Plate

FIGURE 9
 Change in Ultrasonic Critical Angle Signal Amplitude for Irradiated A302-B,
 from Middle of Plate

FIGURE 10
Change in Ultrasonic Critical Angle Signal Amplitude for Irradiated A542-B

range of $\sim 10^{18}$ to 2×10^{20} nvt > 1 MeV for low temperature ($T \approx 140-350$ °F) reactor exposures where $\Delta A_{CA}^i \approx 7.5$ and $\phi t =$ nvt > 1 MeV.

- . Neutron irradiation appears to cause an increase in critical angle signal for high temperature ($T \approx 610-680$ °F) exposures between 2×10^{19} and 2×10^{20} nvt > 1 MeV; but at lesser exposures than used in this study, there may be a decrease in amplitude which is subsequently followed by a reversal in trend to an increase in amplitude. The rate of increase appears to be less than the rate for low temperature irradiated specimens.
- . Despite reasonable scatter and error, the critical angle measurements will detect radiation damage for specimens irradiated to neutron fluences as low as 1 to 3×10^{18} nvt > 1 MeV.
- . Tendencies for saturation starting in the 2 to 5×10^{19} nvt range for low temperature exposed specimens appears to be less than for the ΔV_S and ΔV_L measurements.

DISCUSSION

General

A general similarity between the ΔV curves and ΔA_{CA} curves indicates changes in velocity are a principal cause of changes in critical angle signal amplitude. The similarity of curves also helps establish the credibility of the measurements since one would expect radiation damage to be essentially isotropic thereby causing similar changes in ultrasonic velocities regardless of direction of beam propagation or particle motion.

Where anomalies do exist between shapes of ΔV_S , ΔV_L , and ΔA_{CA} curves for a single family of specimens such as at the 1C1LM, 1C2LM, and 1C3LM data points, the most likely cause(s) are scatter existing in specimens before irradiation, and measurement error. Where similar anomalies exist at similar neutron fluences for all three families such as at the C7 data points, the cause(s) are probably associated with an irradiation parameter(s) such as specimen temperature or energy spectrum of the bombarding neutrons.

Effects of Pre-irradiation Materials Scatter

Scatter was present in all materials but was particularly high for the A302-B material cut from the middle of the donor plate. The nature of the scatter is unknown although some of it is probably related to micro-structural differences as a result of heat treatment parameters.

The presence of scatter, which could not be accurately defined with respect to donor plate position despite possession of unirradiated control specimens from the same plates, caused the data from high temperature irradiated specimens to lose much of their meaning. Although in most high-temperature-irradiated specimens velocities appear to decrease with increased neutron fluence, it cannot be determined with certainty that some velocities had increased relative to unirradiated specimens. A definite knowledge of an increase followed by a decrease in velocities would help establish the nature of the mechanism(s) taking place and their thermal recovery dynamics. Had pre-irradiation velocity measurements been available, thus eliminating scatter, it would have been possible to be more explicit in defining the nature of the high temperature exposed specimens' velocity changes.

Effects of Irradiation Temperature

Although temperature monitor alloys indicated temperatures less than 350 °F for the low temperature groups and between 610 and 680 °F for the high temperature groups, the alloys' behavior in a nuclear environment has not been well established and there is some doubt that actual temperatures were as indicated. For comparison, approximate surface temperatures were calculated and are listed in Table III, Appendix B. An examination of the surface temperatures listing may lead to a partial explanation of anomalies in the curves. In particular, the following associations are noted, based on calculated surface temperature:

- . Temperatures of C1, C2, C3, and C4 specimens were about the same (141-147 °F), but a rather abrupt shift occurs at the C5 specimens (242 °F). In most curves there is a noticeable reduction in the rates of velocities decrease and ΔA_{CA} increase, as functions of fluence, in going from the C4 to C5 specimens.
- . Temperatures of the C7 specimens were significantly higher (285-294 °F) than those of the C5 and C6 specimens (242-224 °F). Again, for most curves, there is a noticeable reduction in ΔA_{CA} and $-\Delta V/V$ in going from the C6 to C7 specimens.

Changes in the high temperature irradiated specimens are small and no consistent anomalous behavior is observed. A consistent anomalous behavior for the H7 group would not be unexpected, however, since surface temperatures in this group were calculated to be much higher (700-739 °F) than in the H4 and H5 groups (557-596 °F). Having approached the 0.34 - 0.37 T_m range (650-750 °F), where T_m = absolute melting temperature, one might expect

differences in elastic properties due to the annealing peak (stress-relieving range) that normally occurs here.

In addition to the calculated surface-temperature differences, calculated differences also exist in the interior of the H7 specimens relative to the H4 and H5 specimens. Gamma heat from the high flux position of the H7 specimens results in a calculated temperature gradient of about 98 °F compared to only 4-29 °F for the H4 and H5 specimens. Elevation of interior temperature to 791-837 °F puts this region close to $0.41 T_m$ (~880 °F), the recrystallization range. One might expect a change in bulk (i.e., throughout specimens' thickness) elastic properties of specimens irradiated at this temperature; surface properties, as measured using the critical angle method, would change less if recrystallization did not extend to the cooler surface. The ultrasonic velocities and critical-angle-method changes in the H7 specimens are too small to allow any conclusions pertaining to recovery at $0.34 T_m$ (or $0.41 T_m$). The absence of any large changes suggests, however, that any recovery taking place at the higher temperatures of the H7 specimens do not significantly affect elastic constants.

Other possible temperature effects could show up particularly on the critical angle individual sides measurements and would be due to slight camber in the enclosure capsule (see Appendix B and Figure 18) causing uneven gaps with, for example, a 0.003 inch gap in the middle on one side and no gap in the middle on the opposite side. The uneven heating might affect recovery and hence surface and subsurface elastic properties. The effect would be less noticeable for ΔV_S and ΔV_L measurements of bulk properties. Still other anomalies from temperature effects could have

been caused by the spacer wires used in the C5 and H7 series specimens or other small direct contact regions which would cool those regions relative to other parts of the specimens.

A higher temperature gradient also exists on the C5, C6, and C7 series specimens relative to the C1, C2, C3, and C4 series specimens (see Table III). This being the case, one might expect a tendency towards flattening out of the ΔV curves due to greater annealing beginning with the C5 specimen ($\sim 5 \times 10^{19}$ nvt) since the ΔV measurements are made on the bulk properties. In contrast, however, surface and subsurface sensitive ΔA_{CA} curves for the same specimens would not flatten out as much since the surfaces of C5, C6, and C7 series specimens remain significantly cooler than their interiors.

As noted in Appendix B and tabulated in Tables XVII, XVIII, and XIX some swelling took place on most specimens. De-encapsulation was difficult on some because of specimens binding on the inside of capsules. Since swelling, in some instances, approximated 10% of the helium gap, some temperature reduction could be expected due to the reduced thickness gap and consequent improved heat transfer.

Effects of Dose Rate and Exposure Time

Dose rate is not thought to be a dominant factor in radiation embrittlement.⁽³⁸⁾ It is known, however, that temperature, flux, and time dependent diffusion controlled reactions take place in alloys.⁽³⁹⁾ Thus, the C4 series specimens, generally showing more changes than expected for the estimated fast flux exposure when compared to the C1, C2, and C3 series specimens, could perhaps have been influenced by the increased time of exposure, nearly three times that of the C1, C2, C3, C5, C6, and C7 series specimens, in reaching the indicated fluence values.

Effects of Neutron Energy Spectrum

Although all data are plotted as a function of fast neutrons (>1 MeV), it is expected that some damage will be caused by lower energy neutrons^(18,40,41) since atomic displacements will take place from collisions with neutrons having energies as low as about 500 eV.⁽⁴²⁾ Thus a more realistic independent variable would encompass the integrated damage causing effects of a broader energy spectrum than >1 MeV. The damaging effects of slow and intermediate energy range neutrons have not been shown, however, to contribute significantly to the total embrittlement.⁽²⁾ The effect on elastic properties could be greater, though, and for this reason the differences in thermal to fast neutron ratios for the different reactor positions used in this study have been listed in Table IV, Appendix B. The data show a significant change in ratios for the C1, C2, C3, and C4 series specimens (9.5:1 to 17.3:1) compared to all the others (1.5:1 to 3.2:1). Thus, perhaps part of the reason for the consistent decrease in $-\Delta V/V$ going from C4 to C5 may be caused by a reduced rate of damage at C5 because of a lesser contribution by neutrons with energies less than 1 MeV. The consistent change in slope between C6 and C7 cannot be accounted for in this manner since both were exposed to about the same energy spectrum.

Effects Related to Specimens' Thickness Position in Donor Plate

Most ΔV measurements indicated slightly more change in the specimens cut from the center of the A302-B plate than those from the top of the plate. Such an observation, if real, would be compatible with observations by others that quenched and tempered materials resist irradiation embrittlement better than normalized or more slowly cooled materials of

identical chemical composition.^(17,42) Hardness measurements (Appendix A) showed very little difference between specimens cut from the center and from the surface of the plate, however, thus indicating similar micro-structure.

Effects Related to Material Composition

No significant differences were noted between the ΔV and ΔA_{CA} measurements on A302-B and A542-B (see Appendix A for composition). Significant differences were noted between the low alloy steels and the austenitic steel (304 SS). Results on 304 measurements will be reported separately.⁽⁴³⁾

Changes in Velocities and Elastic Properties

A discussion of the methods used in taking velocity measurements is found in Appendix E. A discussion of some possible radiation effects on elastic properties is found in Appendix F.

Elastic properties of materials relate to the elastic constants through the equations of motion in an elastic material. Hence, velocity change measurements will enable calculation of changes in elastic constants if densities are known. The results reported herein apply only to the elastic range since the ultrasonic waves used during the study were low amplitude. In addition, the results do not necessarily imply a similar behavior for static measurement methods.

Longitudinal velocity changes were quite small and it is difficult to get an accurate measurement on small specimens. Consequently, the error bands for the ΔV_L measurements were quite large. Shear velocity changes were greater and path length over which the measurements were taken was longer than for the ΔV_L measurements. Error for ΔV_S measurements, then,

was significantly less than for ΔV_L measurements. Despite the large possible scatter and error, the measurements showed good agreement, thus suggesting error is less than shown. It is not possible on the basis of available data to determine quantitatively or qualitatively which of the mechanisms described earlier (STATEMENT OF PROBLEM) have made contributions to the observed velocity changes. Not only are the primary damage state and the thermal recovery mechanisms of irradiated steel still not completely defined, but also the models of elastic behavior in the presence of inhomogeneities are not in good agreement (see Appendix F). One can possibly predict which direction a given mechanism will take a velocity change, but finds such a prediction more difficult in the presence of multiple mechanisms.

Evidence in support of the mechanisms causing decreases in velocities seems to predominate. Interstitials, being more mobile than vacancies, have partly annealed-out to locations where they essentially do not affect elastic properties, whereas vacancy clusters have remained and grown larger and more numerous. Thus the conditions supporting decreases in moduli, or velocities, are present based on elasticity theory, interatomic forces theory, and multiple scattering experiment (for shear waves). In addition, dislocation vibratory length has decreased but dislocation density has increased. The net effect of the dislocations contribution could be to decrease moduli -- due to the greater dislocations density -- if the dislocations do not become so dense as to interact with themselves.

Changes in Critical Angle Signal Amplitude

A discussion of the critical angle method is found in Appendix E. An important difference between the critical angle method and the velocities measurement methods lies in their respective propagation and particle motion directions. Some differences appear in all three methods. Normally, in an isotropic polycrystalline material, the propagation parameters would not make much difference since averaging would occur in any direction. It has been observed, however, that a good amount of scatter exists, particularly in A302-B from the middle of the donor plate, thus making the material anisotropic over the distances involved in ultrasonic measurements. From measurements made on unirradiated control specimens (Tables V, VI, and VII), it is apparent that surface scatter, as determined from ΔA_{CA} measurements, is not always predictable at the same position as bulk scatter as determined from ΔV measurements. Consequently, it is not surprising, for this reason alone, that differences exist between shapes of critical angle curves and velocities curves.

Relationship of Change in Ultrasonic Properties to Shift in Nil-Ductility-Transition-Temperature, NDTT

A comparison of curves of ΔA_{CA} for high and low irradiation temperatures to similar curves for shift in NDTT, both as a function of neutron fluence >1 MeV, is shown in Figure 11.

It is apparent that a reasonably good relationship can be found between ΔA_{CA} (or $\Delta V_S/V_S$, and to a lesser extent, $\Delta V_L/V_L$) and shift in NDTT for low temperature irradiations. Using the same scales on the high temperature irradiations, one finds, however, that the correlation is poor.

FIGURE 11
Effect of Neutron Irradiation on Ultrasonic Critical Angle Signal Response,
and on Nil-Ductility-Transition-Temperature Shift for A302-B Steel

Two possible explanations for the poor correlation at higher temperatures are:

- (1) A significant difference may exist between the NDTT trend at 550 °F and NDTT trend at the temperatures used in this study (estimated to be 610-680 °F, but could vary from ~557 to ~837 °F).
- (2) Ultrasonic methods, at frequencies used in this study, are not very sensitive to the embrittlement mechanism taking place at higher temperatures.

The real situation is probably some of both (1) and (2). If (2) is correct to any extent, then the good correlation at low temperatures must be re-examined with care. If the correlation is the result of some second order effect rather than the mechanical properties degrading effect (embrittlement), then it must be determined what parameters affect only the second order effect but not the mechanical properties.

Laboratory and Field Applications

Any of the three measurement methods described here, as well as surface wave velocity measurements, would have some potential in making damage assessments on irradiated materials. For laboratory studies, the critical angle method has advantages of being somewhat more sensitive to small changes as well as independent of specimen thickness (beyond depth of penetration), and thus less prone to error.

A disadvantage of the critical angle method is that it is surface and subsurface sensitive only; so that in field applications, where access is available only to the exterior of pressure vessels, measurements would be made on a part of the vessel most shielded from radiation damage. Transducer

alignment problems, while not insurmountable, would be difficult. Surface conditions in a pressure vessel are likely to be poor, therefore complicating a critical angle or surface wave velocity measurement. Laboratory conditions could be simulated, however, by conducting measurements on surveillance specimens.

A differential, stabilized instrumentation method could reduce error significantly. Effects of scatter would be essentially eliminated by pre-irradiation measurements on surveillance specimens and by repetitive measurements, over a period of time, on the same specimens as exposure and radiation damage builds up.

For field measurements of structures already irradiated, and if sample sections of the original material are not available, ultrasonic measurements still will provide a good measure of radiation damage for sections kept at lower temperatures. All the measurement methods indicated that, provided error is reduced, apparent changes due to scatter will be less than changes caused by irradiation - even at fluences as low as the threshold fluence for shifts in NDTT (1 to 2×10^{18} nvt >1 MeV).

A possible method for field service would be to measure both shear and longitudinal velocity through the wall thickness of a vessel at a given position on the vessel. Since measurements would be at the exact same position on the vessel, the thickness parameter would vanish and one needs only to follow through on velocity relationships to determine radiation exposure, and hence, radiation damage (at low irradiation temperatures).

More laboratory study would be required to determine the effects of temperature on ΔV recovery before ultrasonics would be useful for measure-

ments on high temperature irradiated steel. Present indications are that ultrasonic velocity changes in steel will not correlate well with radiation degraded mechanical properties when irradiated at temperatures somewhere below about 680 °F but above about 350 °F. Changes in velocities and critical angle signal amplitude are too small both in magnitude for measurement accuracy (unless done on pre-irradiation measured surveillance specimens) and in proportion to expected change in mechanical properties.

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APPENDICES

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APPENDIX A

SPECIMENS PREPARATIONMaterials

Two materials were used: A302-B and A542-B. A302-B was selected for its availability, its wide use in nuclear pressure vessels, and for an abundance of readily available irradiated materials test data. A542-B was selected for its availability and because it is one of several high strength steels now under consideration for inclusion in the ASME Nuclear Code, Section III.⁽⁴⁵⁾ Percentage chemical composition of these materials are as follows:

	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Cu</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>Al</u>
A302-B	0.22	1.33	0.017	0.013	0.30	0.07	0.21	0.12	0.52	
A542-B	0.13	0.39	0.013	0.021	0.30	0.25	0.22	2.44	0.94	0.025

Some mechanical properties of the metals are as follows:

	<u>0.2% Tensile Properties</u>				<u>Impact Properties, Nil Ductility Tran- sition Temperature, °F</u>
	<u>Yield Strength, psi</u>	<u>Ultimate Tensile Strength, psi</u>	<u>Elong- ation, %</u>	<u>Reduc- tion of Area, %</u>	
A302-B, 1/4 T	80,000	98,500	25.5	70.	0 to -40 @ 30 ft-lb
A302-B, 1/2 T	66,000	87,000	25.	72.	+50 to +60 @ 30 ft-lb
A542-B, Surface	103,700	119,400	23.	71.	-33 @ 45 ft-lb
A542-B, 1/2 T	105,800	123,200	22.	67.	+7 @ 35 ft-lb

Typical Rockwell "A" hardness measurements on specimens from each material family, after stress relieving, were: A302-B surface, $R_A \approx 55$; A302-B middle, $R_A \approx 53.5$; A542-B surface, $R_A \approx 62$.

A302-B Mill Specifications

The A302-B specimens were machined from plate no. 190783G, a plate found in the "Irradiations Effects Program" Hanford stockpile. Complete fabrication history of plate no. 190783G can be found in BNWL-CC-236.⁽⁴⁶⁾

In brief, however, processing steps were as follows:

1. Twenty one cross-roll rolling passes were made at 915 °C to 1015 °C in reducing from about ten to four inches thickness.
2. Heated to 900 °C, then water quenched to less than 150 °C.
3. Tempered at 650 °C, then air cooled.
4. Re-tempered at 675 °C, then air cooled.

A302-B Machining

An 8 x 10 inch section was cut from plate no. 190783G and then further sliced so that there were two 8 x 10 inch plates, each 5/8 inch thick--one 5/8 inch plate being from the surface of the original plate and the other being from the middle. Each of these 5/8 inch plates was then cut into six pieces; two of the pieces from each 5/8 inch plate were used as material for 21 test specimens. Orientation of the two pieces were chosen so that the long dimension of the 21 specimens was in the same direction as the predominant rolling direction. Fourteen specimens were cut from three other pieces of each 5/8 inch plate so that the long dimension of the specimens was at 90° to the predominant rolling direction. None of the specimens cut transverse to rolling direction were used during the study due to limited irradiation space. An illustration of the described specimens' orientation is shown in Figure 12.

FIGURE 12
A302-B Test Specimens Orientation Relative to Donor Plate

SPECIFICATIONS

1. Adjacent 0.394 x 2.577 Faces to be Square Within 0.0025 inch/inch (0.15°)
2. Opposite 0.394 x 2.577 Faces to be Flat and Parallel Within 0.0005 inch/inch
3. All 0.394 x 2.577 Faces to have a Surface Finish of 16 Microinches rms or Better

FIGURE 13
Finished Test Specimen

Care was taken during all machining operations to avoid unnecessary metal heating. Nevertheless, a stress relief heat treatment was given all finished specimens except some of the control specimens. Stress relief was one hour at 565 °C in vacuum with furnace cooling. A finished specimen is shown in Figure 13. Identification nomenclature was stamped on one end before finishing machining. Nomenclature identified:

- . type of material,
- . position in plate,
- . direction of predominant rolling,
- . approximate temperature of exposure, and
- . approximate neutron exposure.

The position of each specimen in its donor piece, as shown in Figure 12, is shown in Figures 14 and 15. An explanation of the nomenclature code is found in Appendix B for irradiated specimens and in Appendix D for unirradiated control specimens.

A542-B Mill Specifications

The A542-B specimens were machined from a six inch plate, no. FPX VIP B4274 1, which had been received at Hanford for use in various irradiation experiments.

Processing steps at the mill were briefly as follows:

1. After fabrication into a six inch plate, the plate was heated to 940 °C for six hours, then water quenched.
2. Tempered at 595 °C for six hours, then air cooled.
3. Tempered at 620 °C for six hours, then air cooled.

FIGURE 14
Positions of Test Specimens in Donor Pieces, A302-B from Top of Plate

FIGURE 15
Positions of Test Specimens in Donor Pieces, A302-B from Middle of Plate

A542-B Machining

A 3 x 20 x 6 inch section was cut from the six inch plate and then further sliced so that there was available a 3 x 20 x 3/4 inch plate from the surface with the 3/4 inch dimension in the same direction as the original six inch dimension. The three inch dimension was in the same direction as the predominant direction of rolling. The 3 x 20 x 3/4 inch plate was further cut into three pieces; the largest of the three pieces was used as material for the 22 test specimens all of which were cut so that the long dimension was in the same direction as the predominant rolling direction. Eight specimens were cut from the remaining two smaller pieces so that the long dimension of the specimens was transverse to the predominant rolling direction. None of these eight specimens were used due to limited irradiation space. An illustration of the described specimens' orientation is shown in Figure 16.

A stress relief identical to that given the A302-B specimens was given all A542-B finished specimens except one of the control specimens. Identification nomenclature was stamped on a specimen's end before final machining. The specimen's position relationship to each other is shown in Figure 17. An explanation of nomenclature code is found in Appendix B for irradiated specimens and in Appendix D for unirradiated control specimens.

FIGURE 16
A542-B Test Specimens Orientation Relative to Donor Plate

FIGURE 17
Positions of Test Specimens in Donor Piece, A542-B

APPENDIX B

IRRADIATION OF SPECIMENSNomenclature

An explanation of nomenclature for irradiated specimens (e.g., 1C3LT) is as follows: The first character, a number, identifies type of material; "1" identifies A302-B, "2" identifies A542-B, and "3" identifies 304 stainless steel (304 stainless steel is discussed in another document).⁽⁴³⁾ The second character, a letter, identifies the approximate temperature during irradiation: "C" means cold, or about 140 °F to 350 °F; and "H" means hot, or about 610 °F to 680 °F. The third character, a number, identifies the neutron fluence sequential position; thus "1" identifies the specimen receiving the least exposure and "7" identifies the specimen receiving the highest exposure, etc. The fourth character identifies the mill plate rolling direction, "L" meaning longitudinal and "T" transverse. None of the transverse specimens were used; thus, all tested specimens are "L's" meaning the direction of rolling is in the same direction as the long dimension (2.577 inches) of the specimen. The fifth character identifies position in the plate; i.e., "T" means from the top of the plate and "M" means from the middle of the plate. Two specimens in the A542-B family had a sixth character, a number; these two were irradiated under identical conditions as were two others from the same family with similar characters except for no sixth character.

Not all specimens intended for irradiation were irradiated because of lack of irradiation space. The nomenclature on some of these were altered so that they could be used for control specimens with a minimum of confusion.

Those not irradiated are the H1, H2, H3, and H6 specimens in all families. These specimens were subsequently changed to X1, X2, X3, and X6 respectively. Nomenclature for unirradiated specimens does not adhere to a plan and so are given as listings--in Tables V, VI, and VII in Appendix E.

Encapsulation, Individual Specimens

All irradiated specimens were sealed in 0.035-0.038 inch wall thickness 304 stainless steel capsules. Fabrication of the capsules was accomplished by a reduction drawing of tubing, then inserting a mandrel within the tubing and squaring with a "Turk's Head" machine. In some cases, it was necessary to lightly file the inside corners of the capsules and/or the edges and corners of the specimens so that the two would fit. All capsules were stress-relieved prior to assembly.

A specimen in stages of encapsulation is shown in Figure 18. Assembly was accomplished by welding a cap on one end prior to insertion of a specimen, and then welding the other end of the loaded capsule, using a chill block, while inside a helium glove box which had been evacuated and backflushed with helium at one-atmosphere pressure. After welding, all capsules were helium leak-tested and found to be leak-free.

Two types of caps were used--a button-head as shown in Figure 18, and a square-head as shown in Figure 19. Although more difficult to weld, the square-head cap was considerably cheaper to fabricate.

FIGURE 18
Test Specimens in Various Stages of Encapsulation; Button
Head Cap Shown

FIGURE 19
Test Specimens Being Encapsulated with Wire Spacers; Square
Cap Shown

FIGURE 20
Typical Capsules used for Reactor Ambient Temperature
Positions' Exposures

FIGURE 21
Typical Quadrant Capsules Assemblies used for Reactor G-7
High-Temperature-Loop Exposures

Encapsulation, Capsules Assembly

Two capsules assemblies were used:

1. A cylindrical assembly capable of holding ten specimens as shown in Figure 20, and
2. A quadrant assembly capable of holding three specimens as shown in Figure 21.

The cylindrical assembly was used for all irradiations in the low coolant temperature (C5 and J14 holes) part of the Experimental Test Reactor (ETR), NRTS, Idaho; and the quadrant assembly was used in the high temperature G7 loop. Note, in both assemblies, a small diameter tube, crimped in several plates, welded alongside the encapsulated specimens. The crimped tubing contains the wires used for activation analyses to determine neutron exposure.

A listing of specimens, their capsule number and reactor position, cycle(s) number(s), and fast neutron fluence exposure is given in Table II.

Encapsulation, Heat Transfer Considerations

It is known from work by others that in-reactor annealing of irradiation damage to steel is considerably increased when temperature reaches and exceeds the 450-550 °F region.⁽¹⁷⁾ For this reason, each of the four material families were divided into two groups: 1) low temperature, <350 °F, and 2) high temperature, >600 °F so that the irradiation temperature effect could be independently evaluated.

The H4 and H5 series in all four high temperature groups were irradiated in the high temperature G7 loop of the ETR. Water temperature of the G7 loop is maintained at about 550 °F so that, coupled with the

TABLE IIENCAPSULATION AND IRRADIATION OF TEST SPECIMENS

<u>Capsule Number</u>	<u>Specimen Identification</u>	<u>ETR Cycle(s) Number(s)</u>	<u>Position in ETR</u>	<u>Fast Fluence nvt > 1MeV</u>
GEH14-691 (top)	1C1LT ^(a) 1C1LM ^(b) 2C1LT ^(c) 3C1LT ^(d) C1TH ^(e)	89	C5 1-4 inches from Top	1.47×10^{18}
GEH14-696 (bottom)	1C2LT 1C2LM 2C2LT 3C2LT C2TH	89	C5 5-8 inches from Top	2.78×10^{18}
GEH14-692	1C3LT 1C3LM 2C3LT 3C3LT C3TH	89	C5 19-22 inches from Top	6.79×10^{18}
GEH14-696	1C4LT 1C4LM 2C4LT 3C4LT C4TH	91 & 93	C5 23-26 inches from Top	1.89×10^{19} (f)
GEH14-693 (top)	1C5LT 1C5LM 2C5LT 3C5LT C5TH	90	J14 1-4 inches from Top	5.10×10^{19}
GEH14-693 (bottom)	1C6LT 1C6LM 2C6LT 3C6LT C6TH	90	J14 5-8 inches from Top	1.02×10^{20}

TABLE II (Continued)

<u>Capsule Number</u>	<u>Specimen Identification</u>	<u>ETR Cycle(s) Number(s)</u>	<u>Position in ETR</u>	<u>Fast Fluence nvt > 1 MeV</u>
GEH14-694 (top)	1C7LT	90	J14 19-22 inches from Top	1.88×10^{20}
	1C7LM			
	1H7LT			
	1H7LM			
	H7TH			
GEH14-694 (bottom)	2C7LT	90	J14 23-26 inches from Top	1.75×10^{20}
	3C7LT			
	2H7LT			
	3H7LT			
	C7TH			
GEH20-281	1H4LT	90	G7 X3	1.90×10^{19}
	1H4LM	&		
	H4TH	91		
GEH20-282	2H4LT	90	G7 X1	1.98×10^{19}
	2H4LT2	&		
	3H4LT	91		
GEH20-284	1H5LT	91	G7 A4	1.66×10^{20}
	1H5LM	&		
	H5TH	92		
GEH20-283	2H5LT	91	G7 A1	1.18×10^{20}
	2H5LT3	&		
	3H5LT	92		

Notes

- (a) All 1C LT and 1H LT specimens were cut from the top surface of 4 inch thick A302-B plate #190783G.
- (b) All 1C LM and 1H LM specimens were cut from the middle of 4 inch thick A302-B plate #190783G.
- (c) All 2C LT and 2H LT specimens were cut from the top surface of 6 inch thick A542-B plate # FFX VIP B4274 1.
- (d) All 3C LT and 3H LT specimens were cut from a $\frac{1}{2}$ inch plate # B55697 (further data found in another report, reference 43).
- (e) All C TH and H TH specimens were cut from AISI 1020 steel for use as carriers of temperature monitor wires.
- (f) Estimated fluence for C4 specimens.

gamma heating of the specimen, no difficulty was expected in attaining >600 °F. Since heated capsules were out of the question for cost reasons, advantage was taken of the fact that in the high-flux H7 series position, gamma heating approximates 15 watts per gram. With this rate of heat being generated in the approximately 51 gram specimen, heat transfer could be restricted and controlled to cause the specimen to reach desired temperature. Calculations indicated a 0.010 inch helium gap would cause internal temperature to reach about 700 °F at the surface of the specimen. Since a range of neutron flux levels were anticipated over both the desired temperature levels, to enable flexibility in heat transfer potential, three sizes of capsules were fabricated:

1. 0.396 capsule allowing an approximate 0.0015 inch helium gap,
2. 0.406 capsule allowing an approximate 0.0055 inch helium gap, and
3. 0.416 capsule allowing an approximate 0.0105 inch helium gap.

The H7 series used the 0.416 capsule. An approximately uniform 0.0105 inch gap was maintained on all four sides by inserting on each side a 0.009 inch piece of stainless steel wire, looped on both ends to prevent the wires from migrating together, as shown in Figure 19. A 0.004 inch stainless steel wire was intended for use on the 0.406 capsules.

The 0.406 capsule was used for all C5 series specimens since the mandrel used for fabricating the 0.394 capsules had broken before a sufficient number of capsules had been fabricated. At the time, it was not felt to be of serious consequence because the reactor's C5 position is a low flux region, and internally generated gamma heat was thought to be too low to significantly affect the specimen temperature. 0.004 inch

diameter wires were used in all C5 series specimens to enable uniform gap spacing on all four sides.

The C4 series specimens were the last group to be prepared for irradiation and, again, the 0.406 capsule was used due to a lack of 0.396 capsules. Instead of using wires as spacers, however, 0.004 inch flat carbon steel shim stock were used as spacers. With flat shim stock instead of wires in the helium gap, heat transfer was considerably improved thus reducing the in-reactor annealing of irradiation damage. It is regretted that shim stock was not used for the C5 series also since the higher irradiation temperature of the C5 series may have enabled increased annealing of the irradiation damage.

Temperature Monitors

Although it was possible to calculate approximate specimen temperature during irradiation, a more positive method of determining temperature was desired to help validate results. Temperature monitor wires were available covering temperatures above 312 °F, and since no better method as fast and as cheap could be found, the wires were used. Temperature monitors used were 0.062 inch diameter wires of various elements and alloys which melt at known temperatures.

The technique used was to imbed four to six different wires in a dummy carbon steel specimen which was then encapsulated the same as the test specimens and mounted alongside them in the specimen's capsule. After irradiation, when the capsules were opened, the dummy specimens were visually examined through a lead glass window to see which wires had melted.

The method of imbedding the wires was to: 1) place a 1/8 inch long wire in a 1/16 inch diameter x 1/2 inch long hole, drilled at an angle to the surface and into which a short thin steel wire had been placed to prevent the temperature monitor from falling completely within, and 2) dimple the exposed end of the temperature monitor in place with a center punch.

The specimens were mounted in their capsules so that gravity would cause melted wires to flow down into the holes.

Figure 22 shows an example of a group of dummy specimens before and after irradiation. In some holes, the monitor wire apparently melted and under the force of gravity flowed down into the hole as expected. In other holes, the wire stayed in place but apparently got mushy and changed appearance; others remained visibly unchanged from their pre-irradiation appearance.

Lack of coverage below 312 °F was unfortunate since five of the seven "C" series specimens indicated irradiation temperatures less than 312 °F, and the data suggests that a significant temperature variation existed among these five specimens groups.

Table III shows calculated approximate temperature at the surface and in the center interior of the specimens as compared to the temperature range indicated by the monitor wires. The anomalous results cannot be accounted for at this time. The primary objective seems to have been met, however, in that according to the temperature monitors, one group--the "C" series--were irradiated at temperatures below 350 °F, while the second group--the "H" series--were irradiated at temperatures above ~600 °F.

 $T < 312^{\circ}\text{F}$

 $312 < T < 349^{\circ}\text{F}$

 $312 < T < 349^{\circ}\text{F}$

 $610 < T < 680^{\circ}\text{F}$

 $610 < T < 680^{\circ}\text{F}$

 $610 < T < 680^{\circ}\text{F}$

Numbers Between Specimens Indicate Melting
Temperatures in $^{\circ}\text{F}$ for Temperature Monitors

T = Indicated Irradiation Temperature

FIGURE 22
Six Temperature Monitor Specimens:
Before Irradiation on Left; After Irradiation on Right

TABLE IIIINDICATED AND CALCULATED IRRADIATIONTEMPERATURE DATA ON TEST SPECIMENS

Test Speci- mens Series	Width of Helium Gap in.	Fast Flux nv $\times 10^{14}$	Estim. Gamma Heat watt/gm.	Coolant Water Temp. °F	Estim. Inter. Temp. (Calcu- lated) °F	Estim. Surface Temp. (Calcu- lated) °F	Indicated Surface Temp., T, (Temp. Monitors) °F
C1	0.0015	0.0081	0.116	140	142	141	T<312
C2	0.0015	0.0153	0.224	140	144	143	T<312
C3	0.0015	0.0373	0.535	140	149	145	T<312
C4	0.0025	0.0354	0.506	140	150	147	T<312
C5	0.0055	0.2850	4.08	140	270	242	T<312
C6	0.0015	0.5700	8.15	140	277	224	312<T<349
C7, 1LT & 1LM	0.0015	1.049	15.0	140	392	294	312<T<349
C7, 2LT & 3LT	0.0015	0.980	14.0	140	376	285	312<T<349
H7, 1LT & 1LM	0.0105	1.049	15.0	140	837	739	610<T<680
H7, 2LT & 3LT	0.0105	0.980	14.0	140	791	700	610<T<680
H4, 1LT & 1LM	0.0015	0.0454	0.650	550	561	557	610<T<680
H4, 2LT & 3LT	0.0015	0.0472	0.675	550	561	557	610<T<680
H5, 1LT & 1LM	0.0015	0.312	4.46	550	625	596	610<T<680
H5, 2LT & 3LT	0.0015	0.221	3.16	550	603	582	610<T<680

Neutron Monitors

Neutron monitors consisted of four wires, Fe, Ni, Ti, and Al-Co, sealed in a crimped stainless steel tube. Each of the seven "C" series and five "H" series capsules assemblies had a neutron monitor. Approximate neutron flux exposure is determined by activation analyses of the four wires. The Fe, Ni, and Ti wires are used to determine fast flux (>1 MeV) and the Al-Co wire is used to determine thermal flux (2200 m/s). Activation analysis was performed at NRTS, Idaho.

Table IV shows a compilation of irradiation data. The data for C4 series is estimated; estimates are based on data from the C3 series in an earlier cycle at the approximate same position in the reactor. C4 series was the most recently irradiated series and activation counting has not yet been performed. Table IV includes corrected figures which take into account the position of each wire with respect to the center of the test specimens. Such a correction is necessary as steep flux gradients exist at many of the irradiation positions. The corrected figure is the average flux at the center of the specimen as indicated by the Fe and Ni wires for fast flux and the Al-Co wire for thermal flux.

De-encapsulation

Specimens capsules were removed from the capsules assemblies, and the specimens were removed from the capsules at the Radiometallurgy facility at Hanford. In most cases, the specimens were removed from their capsules on a lathe by cutting off caps on both ends and then simply pushing out the specimens. In some specimens, however, swelling had been great enough that the specimens were pushed out of their cladding only with

TABLE IV

NEUTRON IRRADIATION DATA ON TEST SPECIMENS

Test Speci- mens Series	Indic- ated Fast Flux Fe Wire, nv x 10 ¹⁴	Indic- ated Fast Flux Ni Wire, nv x 10 ¹⁴	Ave. of cor- rected Fast Flux, nv x 10 ¹⁴	Indic- ated Thermal Flux Al-Co Wire, nv x 10 ¹⁴	Cor- rected Thermal Flux, nv x 10 ¹⁴	Eff. Irrad. Time, Sec, x 10 ⁶	Fast Fluence >1 MeV, nvt ₁₈ x 10 ¹⁸	Thermal Fluence 2200 m/sec., nvt ₁₈ x 10 ¹⁸	Thermal to Fast Flux Ratio
A11 C1	0.0070	0.0080	0.0081	0.102	0.098	1.82	1.47	17.8	12.1:1
A11 C2	0.0137	0.0148	0.0153	0.153	0.145	1.82	2.78	26.4	9.5:1
A11 C3	0.0361	0.0378	0.0373	0.633	0.645	1.82	6.79	117.3	17.3:1
A11 C4*	0.0345	0.0362	0.0354	0.569	0.580	5.35	18.9	310.0	16.4:1
A11 C5	0.2220	0.2490	0.2850	0.934	0.882	1.79	51.0	158.0	3.1:1
A11 C6	0.5280	0.5200	0.5700	1.68	1.62	1.79	102.0	290.0	2.8:1
1LT, 1LM C7 & H7	1.080	0.9790	1.049	2.81	2.82	1.79	188.0	505.0	2.7:1
2LT, 3LT C6 & H7	1.060	0.9500	0.9800	3.07	3.13	1.79	175.0	560.0	3.2:1
1LT, 1LM H4	0.0355	0.0411	0.0454	0.138	0.119	4.19	19.0	49.9	2.6:1
2LT, 3LT H4	0.0352	0.0446	0.0472	0.139	0.120	4.19	19.8	50.3	2.5:1
1LT, 1LM H5	0.2380	0.2890	0.3120	0.552	0.475	5.34	166.0	254.0	1.5:1
2LT, 3LT H5	0.1760	0.1960	0.2210	0.490	0.421	5.34	118.0	224.0	1.9:1

* Estimated

B-14

BNWL-988

considerable difficulty resulting in some damage to the specimen. In another capsule, the wire spacers jammed during specimen removal. Following a few of these experiences, it was decided to cut the edges off the capsules in addition to turning off the caps thus reducing the forces squeezing the specimen inside the capsule. This technique worked best when a slitting saw made a longitudinal cut along an edge.

All capsules retained their seal integrity during irradiation. All de-encapsulated specimens were clean, bright, and with no other visual evidence of chemical reaction.

APPENDIX C

MEASUREMENT APPARATUSMechanical Equipment

The test tank, shown in Figure 23, is a model of a design used at Hanford Laboratories and Pacific Northwest Laboratories for several years. It satisfies many of the pre-requisites for rapid, accurate, and reproducible measurements. Some of its features, particularly useful for radioactive materials are:

- . Specimens may be loaded and unloaded remotely, i.e., by a master-slave manipulator.
- . Specimens are supported above the test crystals thus enabling a constant crystals to specimen-surface relationship despite variations in specimen dimensions.
- . Six different position adjustments are available on the specimen holder; five adjustments are available on each transducer holder. Additional motions are available on one of the large half-circle goniometers and also on the entire specimen holder sub-assembly.
- . Glass walls enable easy viewing, adjustments, etc.

Other test tank features used in this study are a water cooler, a water heater, and a recirculating, filtered water supply. A constant temperature was found to be essential for accurate measurements.

Initially, water was kept at about 15-17 °C for the purpose of inhibiting algae growth. When it became apparent that heat transfer into the water from one's hand and arm, immersed in the water for making adjustments,

FIGURE 23
Immersion Facility for Ultrasonic Measurements on Irradiated
Test Specimens

would cause false settings, the water temperature was raised to room temperature, $\sim 21^\circ\text{C}$. Thereafter, the cooler and heater were used only on occasion when it was desired to arrive at some particular temperature. Once the basic temperature was reached, heater/cooler and recirculating pump were turned off. A remotely-operated speedometer cable was used for making one goniometer adjustment. When such adjustments were necessary, not only did the speedometer cable enable avoiding heat transfer into the water from a hand-arm, but also saved the hand-arm unnecessary radiation exposure.

Electronic Equipment

Descriptions of the electronic equipment are found under measurement methods of Appendix E. A block diagram for set-ups when taking velocity measurements is shown in Figure 29. A block diagram of a set-up for critical angle method measurements is shown in Figure 37. This set-up allowed averaging of the critical angle signal amplitude, A_{CA} , over a selected length (center 1 inch) of a test specimen while the test specimen was translated past the fixed crystals; and also enabled a chart recording of instantaneous signal amplitude and integrated signal amplitude.

Due, in part, to a limited linear dynamic range of the integrating instrumentation, RF signal amplitude measurements were also taken on all specimens, using the set-up shown in Figure 38, with a calibrated oscilloscope. An integrating effect is obtained by taking several RF measurements and averaging the results. After normalizing, it is seen that averaged RF measurements yield essentially the same results as the

integrated measurements. Somewhat greater accuracy is attributed to the integrated scans since scatter tends to average-out.

Electronic chassis used for velocity measurements were a commercially available pulse-echo flaw detector and wide-band amplifier. Electronic chassis used for critical angle method measurements were locally designed and fabricated except for the oscillator, oscilloscope and recorders.

Transducers used throughout all measurements were 3.2-4.8 MHz PZT5A 3/16 inch diameter crystals. Flat-lens crystals were used for most measurements. Radiation damage to the lens of one transducer forced substitution of a two-inch focal length transducer for one of the flat lens transducers. Most critical angle RF amplitude measurements reported used one flat and one focused crystal.

APPENDIX D

SHIELDED MATERIAL FACILITY

Weight of individual test specimens approximated 50 to 52 grams, and dose rate for each varied from several hundred mr/hr to several R/hr at one foot. Since 42 irradiated specimens, ten of which were highly radioactive 304 stainless steel, were on hand for measurements, a shielded facility was needed both for working and storing the specimens. Except for preliminary measurements made in a small lead brick laboratory facility, all measurements were made at Hanford's 324 Building Shielded Material Facility. Specimen storage was within a large five-cylinder, rotating-drum, lead-filled cask appropriately called the Gatling Gun Cask.

Hot Cell

Shielding is provided by four feet of high density concrete. Two master-slave manipulators and a large lead-glass shielded window serve the interior working area. The ultrasonic test tank facility is positioned close to the window as shown in Figure 24. Nearby is a stand which supports a small lead cave and auxiliary apparatus such as an ultrasonic cleaner. The lead cave is used to provide shielding for personnel desiring to enter the cell during measurements taking periods. The lead cave plus a small lead cask within the cave limits dose rate in the immediate area to less than 10-15 mr/hr when a family of specimens is stored within. In back of the test tank lies the Gatling Gun Cask.

FIGURE 24
Hot Cell Specimen Handling Area seen Through High Density
Glass Window

FIGURE 25
Gatling-Gun Specimens-Storage-Cask

Specimens Storage, Gatling Gun Cask

Each of the four material families of specimens is separately stored in a small aluminum container as shown in Figure 24. Each container is designed so that it may be readily remotely loaded and unloaded with specimens and in turn loaded and unloaded in a cylinder of the Gatling gun cask as shown in Figure 25. Part of the Gatling gun loading and unloading must be done by the operator within the cell. The cask, however, lies between the specimens and the operator providing complete shielding except for scatter. The operator, nevertheless, keeps a respectable distance and handles the aluminum container with a long rod inserted through a bore in the cask.

The Gatling gun cask reduces dose rate in the immediate vicinity to about 3 mr/hr when all 42 specimens are inside.

Test Tank as a Shield

Occasional crystal alignment adjustments were necessary while ultrasonically examining an irradiated specimen. At other times, it became necessary to directly retrieve a dropped specimen or adjust its position on the specimen holder although these could usually be done remotely. It was found that, except for the stainless steel specimens, the tank water would provide adequate shielding for the short periods of time involved.

APPENDIX E
MEASUREMENTS METHODS

Control Specimens

It was known that the irradiated test specimens would experience a wide range of temperature during irradiation due to "gamma heating" and because of their being encapsulated. The helium gap between the specimen and the capsule acts as a thermal resistance to heat generated within the specimen as a result of the gamma flux environment. Heat generated by the specimen builds up due to the helium gap thermal resistance; but as it builds up, the rate of heat transfer increases until finally an equilibrium is reached where heat transferred out is equal to the heat generated. The temperature at this equilibrium will be higher at the higher neutron flux positions where more gamma heat is generated.

To determine the effects of temperature on the irradiated specimens, a group of control specimens, for each material family, were cut from plate positions adjacent to the specimens used for irradiation, and then subjected to three weeks (1.81×10^6 seconds) of heat treatment over a range of temperatures from 200 °F through 800 °F in 100 °F increments. All the control specimens were encapsulated in one-atmosphere-helium stainless steel capsules prior to heat treatment.

No measurements were made on specimens before heat treatment since measurements apparatus was not yet available at the time the heat treatments were scheduled to start. Measurements made subsequent to heat treatment revealed a fair amount of scatter. The patterns of scatter, and comparisons against specimens not heat treated, indicated, however,

that most of the scatter was present in the material before heat treatment. In any event, the amount of scatter was small relative to the amount of change due to irradiation except for measurements on low dosage specimens, some of the ΔV_L measurements, and all measurements on high temperature irradiated specimens.

A tabulation of $\Delta V_S/V_S$, $\Delta V_L/V_L$, and ΔA_{CA} for the three material families are shown in Tables V, VI, and VII. An illustration defining positions and sides of a test specimen is found in Figure 26. The main purposes of taking readings on the control specimens were to help establish the width of the scatter bands and determine the starting planes for changes due to irradiation. For example, the reference standard 1UOLM proved to have decreased velocities relative to most other control specimens; in contrast, the reference standard 2UOLT proved to have increased velocities relative to most other control specimens. These variations are taken into account and separated--in part--from the measurements taken on the irradiated specimens so that the resultant velocity figures are more closely representative of only changes due to irradiation. A description of how the measurements of the control specimens were used to supplement the irradiated specimens measurements is given in Appendix E under the applicable measurement method.

Some observations relative to the controls specimens are:

- . The specimens showing increased shear velocities often showed increased longitudinal velocities at the same positions; the same is true for decreased velocities. Notable examples of this behavior are 2LT1, 2X1LT, 2AOLT, 1LM2, 1X1LM, 1LM4, 1LT1, and 1LT3.

TABLE V

CHANGES IN SHEAR VELOCITY, LONGITUDINAL VELOCITY, AND
CRITICAL ANGLE SIGNAL AMPLITUDE FOR A302-B
CONTROL SPECIMENS (FROM SURFACE OF PLATE)

Speci- men Identi- fication	Heat Treat- ment for 3-Weeks, °F	Change in Shear Velocity, $\Delta V_S/V_S$ (b,c)			Change in Longitudinal Velocity, $\Delta V_L/V_L$ (b,c)		
		Posi- tion	Posi- tion	Posi- tion	Ave. of Posi- tions	Ave. of Posi- tions	Ave. of Posi- tions
		1-4, %	2-5, %	3-6, %	1&4, %	2&5, %	3&6, %
1LT1	As Ma- chined	-.039	-.016	-.015	-.018	-.005	-.021
1NOLT	Stress Relief Only	-.023	-.016	+.009	+.001	-.020	-.010
1X3LT	Stress Relief Only	-.007	-.003	+.022	-.009	-.005	-.004
1X6LT	Stress Relief Only	+.002	+.014	+.023	+.002	+.017	+.004
1UOLT ^(a)	200	0	0	0	0	0	0
1LT2	300	-.023	-.036	+.003	-.015	-.035	-.009
1LT3	400	-.106	-.085	-.028	-.049	-.033	-.013
1X1LT	500	-.012	0	0	-.012	-.015	0
1X2LT	600	0	-.002	+.021	+.005	+.005	+.020
1A0LT	700	+.029	+.030	-.004	+.006	-.010	+.008
1LT4	800	-.012	-.025	-.002	-.042	-.016	-.012

TABLE V (Continued)

Specimen Identi- fication	Critical Angle Signal Amplitude, ΔA_{CA} ^(b,c,d)				
	Side 1 Pos. 2, v	Side 2 Pos. 5, v	Side 3 Pos. 2, v	Side 4 Pos. 5, v	Ave. All Pos., v ₁
1LT1	-.7	+.8	+.4	-1.7	-.30
1NOLT	-.7	+.4	+.2	+.5	+.10
1X3LT	+.1	+.5	+.2	-.7	+.02
1X6LT	+.3	+.3	0	+.4	+.25
1UOLT ^(a)	0	0	0	0	0
1LT2	+.1	+.8	+.8	+.7	+.60
1LT3	0	+.3	-.5	-1.9	-.52
1X1LT	-.2	+.3	+.3	+.2	+.15
1X2LT	0	-.2	+.9	-.5	+.05
1AOLT	-.2	-.2	+.5	+.2	+.07
1LT4	+.3	-.2	+.8	-1.2	-.07

Notes: (a) Specimen 1UOLT used as reference for all measurements.

(b) A + reading designates an increase in velocity or signal amplitude relative to the same measurement at a similar position on 1UOLT.

(c) A - reading designates a decrease in velocity or signal amplitude relative to the same measurement at a similar position on 1UOLT.

(d) v, v₁ = an arbitrary unit of RF voltage amplitude.

TABLE VI

CHANGES IN SHEAR VELOCITY, LONGITUDINAL VELOCITY, AND
CRITICAL ANGLE SIGNAL AMPLITUDE FOR A302-B
CONTROL SPECIMENS (FROM MIDDLE OF PLATE)

Speci- men Identi- fication	Heat Treat- ment for 3-Weeks, °F	Change in Shear Velocity, $\Delta V_S/V_S$ (b,c)			Change in Longitudinal Velocity, $\Delta V_L/V_L$ (b,c)		
		Posi- tion 1-4, %	Posi- tion 2-5, %	Posi- tion 3-6, %	Ave. of Posi- tions 1&4, %	Ave. of Posi- tions 2&5, %	Ave. of Posi- tions 3&6, %
1LM1	As Ma- chined	-.015	+.043	+.017	+.012	+.023	+.030
1NOLM	Stress Relief Only	-.009	-.013	+.010	+.005	+.008	+.025
1X3LM	Stress Relief Only	-.015	-.002	-.004	-.018	+.011	0
1X6LM	Stress Relief Only	-.008	+.056	-.015	-.018	+.010	+.027
1UOLM ^(a)	200	0	0	0	0	0	0
1LM2	300	+.093	+.139	+.111	+.095	+.080	+.117
1LM3	400	+.033	+.030	+.028	+.004	+.028	+.015
1X1LM	500	+.102	+.142	+.119	+.112	+.142	+.132
1X2LM	600	-.002	+.020	0	+.004	0	-.005
1AOLM	700	-.007	+.027	+.040	+.005	+.019	+.025
1LM4	800	+.010	+.041	+.048	+.024	+.049	+.024

TABLE VI (Continued)

Specimen Identi- fication	Critical Angle Signal Amplitude, ΔA_{CA} ^(b,c,d)				
	Side 1	Side 2	Side 3	Side 4	Ave.
	Pos. 2, v	Pos. 5, v	Pos. 2, v	Pos. 5, v	All Pos., v ₁
1LM1	+1.3	-1.3	0	+0.5	+0.12
1NOLM	+1.3	-1.0	-0.4	+1.6	+0.42
1X3LM	+1.7	+1.0	+0.3	+0.5	+0.88
1X6LM	-0.3	-1.3	-0.2	+0.6	-0.30
1UOLM ^(a)	0	0	0	0	0
1LM2	+0.2	+2.5	0	+3.0	+1.42
1LM3	+0.5	-1.5	+0.2	+0.5	-0.07
1X1LM	0	-1.7	0	+0.7	-0.25
1X2LM	+1.2	-1.5	+0.3	+0.5	+0.12
1AOLM	-0.5	-1.7	+0.4	+0.3	-0.38
1LM4	0	-2.0	-0.3	+0.3	-0.50

Notes: (a) Specimen 1UOLM used as reference for all measurements.

(b) A + reading designates an increase in velocity or signal amplitude relative to the same measurement at a similar position on 1UOLM.

(c) A - reading designates a decrease in velocity or signal amplitude relative to the same measurement at a similar position on 1UOLM.

(d) v, v₁ = an arbitrary unit of RF voltage amplitude.

TABLE VII

CHANGES IN SHEAR VELOCITY, LONGITUDINAL VELOCITY, ANDCRITICAL ANGLE SIGNAL AMPLITUDE FOR A542-BCONTROL SPECIMENS

Specimen Identi- fication	Heat Treat- ment for 3-Weeks, °F	Change in Shear Velocity, $\Delta V_S/V_S$ (b,c)			Change in Longitudinal Velocity, $\Delta V_L/V_L$ (b,c)		
		Posi- tion	Posi- tion	Posi- tion	Ave. of Posi- tions	Ave. of Posi- tions	Ave. of Posi- tions
		1-4, %	2-5, %	3-6, %	1&4, %	2&5, %	3&6, %
2LT1	As Ma- chined	-.058	-.058	-.060	-.039	-.020	-.038
2NOLT	Stress Relief Only	-.058	-.058	-.039	-.028	-.005	-.025
2X6LT	Stress Relief Only	-.006	+.012	+.002	+.004	+.021	-.006
2UOLT ^(a)	200	0	0	0	0	0	0
2LT4	300	-.006	-.020	-.015	-.010	-.005	-.005
2LT5	400	-.022	-.013	-.016	-.006	+.010	+.005
2X1LT	500	-.065	-.052	-.058	-.030	-.010	-.021
2X2LT	600	-.065	-.063	-.068	-.012	+.001	-.030
2A0LT	700	+.029	+.038	+.046	+.035	+.040	+.046
2X3LT	800	-.030	-.043	-.049	+.001	+.010	-.015

TABLE VII (Continued)

Specimen Identi- fication	Critical Angle Signal Amplitude, ΔA_{CA} ^(b,c,d)				
	Side 1	Side 2	Side 3	Side 4	Ave.
	Pos. 2, v	Pos. 5, v	Pos. 2, v	Pos. 5, v	All Pos., v ₁
2LT1	-.2	+.4	+.4	0	+.15
2NOLT	+.4	+1.6	+.4	+.3	+.67
2X6LT	-.2	+.1	-.3	+.4	0
2UOLT ^(a)	0	0	0	0	0
2LT4	+.8	-.2	+.3	+.2	+.28
2LT5	0	+.6	-.3	0	+.07
2X1LT	-.4	+1.1	+.3	0	+.25
2X2LT	-.2	+1.2	+1.2	+.5	+.67
2AOLT	-.1	0	-.3	-.1	-.12
2X3LT	-.3	+.1	-.3	+.5	0

Notes: (a) Specimen 2UOLT used as reference for all measurements.

(b) A + reading designates an increase in velocity or signal amplitude relative to the same measurement at a similar position on 2UOLT.

(c) A - reading designates a decrease in velocity or signal amplitude relative to the same measurement at a similar position on 2UOLT.

(d) v, v₁ = an arbitrary unit of RF voltage amplitude.

FIGURE 26
Example of Sides and Positions Location, both Irradiated and Unirradiated
Controls Specimens

- . There was no clearly discernible tendency for specimens heat treated at high temperatures to show a trend in change in velocities relative to those heat treated at low temperatures.
- . Some tendency for grouping, with respect to position in the donor plate, was in evidence; this tendency was too small on longitudinal velocity measurements to form any conclusions with respect to irradiated specimens cut from positions adjacent to the control specimens. The grouping tendency was great enough on shear velocity measurements, however, that a correction was made to irradiated specimens' shear velocities based on their original position in the donor plate. The methods used to make scatter corrections are more fully discussed under Measurement of Change in Shear Velocity, ΔV_S , Appendix E.
- . No particular correlation was noted between critical angle measurements and velocity measurements. Part of the reason for little correlation is due to error in making measurements of very small changes. Other reasons may be related to the different modes of wave propagation, i.e., the ΔV_L and ΔV_S measurements are sensitive to bulk properties whereas the ΔA_{CA} measurement is sensitive only to surface properties. In addition, since directions of propagation and particle motion are different for the three measurements, any anisotropy would show up as some disagreement among the three modes.

Preparation of Irradiated Specimens for Measurements

Due to swelling, several specimens were scratched or otherwise marred as they were being removed from their capsules. The extent of the marring was not realized until the specimens were micrometer measured. Several specimens measured up to 0.002 to 0.003 inch larger on a cross-section dimension than when measured before irradiation, a figure obviously too high. A closer visual examination, using an astronomer's telescope, revealed occasional scratches and burrs. To restore the marred surfaces to their original flat surface, the marred specimens were gently sanded on fine wet-or-dry silicon carbide paper immersed in mineral oil. When repeated micrometer measurements showed no further reduction in dimension after a series of 10 or 15 passes on the sandpaper, the sanding was stopped. Repetitive measurements on the same specimen showed reproducible readings within ± 0.0001 inch.

Only a few measurements of length were made; percentage change in length was in the same order or magnitude as was percentage change in cross-section dimension.

Measurement of Change in Shear Velocity, ΔV_S

Ultrasonic Method

The test facility was most suitable for immersion type measurements. Since a non-viscous liquid cannot conduct a shear wave, a method was selected whereby an incident longitudinal-wave pulse was mode-converted to a shear-wave pulse. Then, as in an acoustic delay line, the shear-wave pulse bounces around the interior of the test specimen until finally because of attenuation, dispersion, non-parallel sides, absorption, and

mode-conversions and subsequent interferences, etc., the original pulse loses its identity.

See Figure 27 for an illustration of the approximate travel path of the peak amplitude portion of the pulse. A transmit pulse of several damped oscillations is directed to the test specimen at an incident angle of about 19° . A mode conversion to a 45° shear wave takes place, but the greater part of the incident pulse is directly reflected to a receive crystal also aimed at about 19° . The directly reflected echo, as received by the receive crystal, becomes the reference point in time for measurements to subsequent pulses which have made one or more circuits within the specimen. A portion of the energy reconverts to longitudinal energy at each face and travels out into the water. Only that part which refracts at the original incident face is of interest for it can be directly compared to the original surface reflection. In this manner, it is possible to obtain up to ten or eleven circuitous reverberations before signals become too garbled to identify. A photo of waveforms of echoes having traveled within a typical test specimen is shown in Figure 28.

Although greater measurement accuracy can be obtained by measuring changes taking place in the tenth or eleventh reverberation, the possible error due to pulse distortion becomes greater. Accordingly, a compromise was made and all measurements were made with respect to the fifth reverberation. The method of measurement was to:

1. line up a clean, fast rise-time portion of the fifth reverberation of the reference specimen on a reference vertical line of an oscilloscope graticule,

FIGURE 27

Method of Transducers Set-up for Measuring Shear Velocity Changes in Irradiated and Unirradiated Specimens

Time Base = 10 Microseconds/Large Division

FIGURE 28

Shear-Wave-Pulse Reverberations from Traveling Within Test Specimens

2. replace the reference specimen with an irradiated specimen, and
3. measure the time distance, ΔT_S , from the reference vertical line to a point on the echo waveform which corresponds to the reference point on the reference specimen's waveform.

Electronics

See Figure 29 for a block diagram of the measuring circuits. A delayed sweep oscilloscope was used in which the delaying sweep was triggered by the gated surface-echo. The time position of the main sweep trigger is set internally on the oscilloscope using the delay potentiometer, so that the main sweep begins at about the same time the fifth reverberation arrives. The time base of the main sweep was set at 0.2 microsecond per centimeter which results in a resolution of 0.04 microsecond per small graticule division. A series of fifth (and some fourth) reverberations waveforms appear in Figure 30. In all cases, the unirradiated reference waveform is at the top. Photographs of 1C1LM and 1C3LM are unavailable. The smaller amplitude signal in the double-exposure 1C6LM photograph should be ignored. Time base in all photos is 0.2 microsecond per centimeter. All measurements were taken on the right hand seven centimeters of the graticule--a section found to be linear. Center frequency of the received pulse is about 2.5 MHz.

Data Reduction

All change-in-time readings, ΔT_S , must be corrected for dimensional variations among specimens. Most irradiated specimens lay within a dimensional range of about 0.0004 inch, and micrometer measurement accuracy

FIGURE 29
Block Diagram of Electronic Circuits used for Measuring Changes in Shear or Longitudinal Velocities

Top: 1LM3 Fifth Reverberation
Bottom: 1C2LM Fifth Reverberation

Top: 1LM3 Fourth Reverberation
Bottom: 1C7LM Fourth Reverberation

Top: 1LM3 Fourth Reverberation
Bottom: 1C4LM Fourth Reverberation

Top: 1LM3 Fifth Reverberation
Bottom: 1H4LM Fifth Reverberation

Top: 1LM3 Fifth Reverberation
Bottom: 1C5LM Fifth Reverberation

Top: 1LM3 Fifth Reverberation
Bottom: 1H5LM Fifth Reverberation

Top: 1LM3 Fifth Reverberation
Bottom: 1C6LM Fifth Reverberation

Top: 1LM3 Fourth Reverberation
Bottom: 1H7LM Fourth Reverberation

Time Base, All Photos = 0.2 Microsecond/Large Division

FIGURE 30
Shear Wave Waveforms: Irradiated Specimens Relative to
Unirradiated Specimen

was found to be about ± 0.0001 inch. Each irradiated specimen was micrometer measured in six positions (see Figure 26). The variations in dimensions relative to the reference standards (the "U0" specimens) were converted to percentages and then used to modify the $\Delta V_S/V_S$ data calculated from the $\Delta T_S/T_S$ data.

Scatter and Error

Many additional measurements and calculations were necessary to reduce error and scatter, since pre-irradiation measurements had not been taken.

Some error reduction has probably been effected by measurements on control specimens and then extrapolating these measurements to the irradiated specimens. Measurements on the control specimens enable an approximate determination of 1) a reference plane upon which to base the irradiated specimens measurements, and 2) the width of the scatter band about the adjusted irradiated specimens measurements.

Error is determined separately and is distinguished from scatter in being caused by 1) error in micrometer measurements, 2) drift and inaccuracies in electronic circuits, and 3) error related to the ultrasonic method.

Corrections for Scatter

A correction $\Delta V_S/V_S$ figure for each irradiated specimen was determined by converting all measurements on irradiated and control specimens to a common standard (the "U0" specimens), and then extrapolating a correction figure to the irradiated specimen measurement based on the known velocity measurements (see Tables V, VI, and VII) of its unirradiated control

specimen neighbors. For example, at positions 2-5 (see Figure 26), $\Delta V_S/V_S$ for 1X6LT is +0.014% and for 1A0LT is +0.030% greater than for 1U0LT (see Table V). Specimen 1C6LT came from between 1X6LT and 1A0LT, so by extrapolation, a correction $\Delta V_S/V_S$ figure of +0.022% was subtracted from the measured $\Delta V_S/V_S$ for 1C6LT when 1U0LT is used as the reference. Thus the corrected figure becomes -0.672% instead of -0.650%.

Tables VIII, IX, and X show, for irradiated specimens, a tabulation of:

1. change in shear velocity, already corrected for dimensional variations, for each of the three measuring positions,
2. change in shear velocity, corrected for estimated scatter, for each of the three measuring positions, and
3. an averaged change in shear velocity, $\Delta V_S/V_S$, of all three scatter-corrected measurements (the final values used for plotting the curves shown in Figures 2, 3, and 4).

Scatter Band Width

The scatter band width is the difference between the maximum averaged positive and maximum averaged negative $\Delta V_S/V_S$ readings for the unirradiated control specimens for each family.

- For the 1LT family, the specimen which has the highest averaged positive $\Delta V_S/V_S$ is 1A0LT, +0.018%; highest averaged negative $\Delta V_S/V_S$ is 1LT3, -0.073%. Scatter band width = $0.018 - (-0.073) = 0.091\%$

TABLE VIII

CHANGE IN SHEAR VELOCITY FOR IRRADIATED A302-B, FROM TOP OF PLATE

Specimen Identi- fication	$\Delta V_S/V_S$			$\Delta V_S/V_S$	$\Delta V_S/V_S$	$\Delta V_S/V_S$	Average
	Position 1-4 %	Position 2-5 %	Position 3-6 %	Position 1-4 Scatter Cor- rected, %	Position 2-5 Scatter Cor- rected, %	Position 3-6 Scatter Cor- rected, %	$\Delta V_S/V_S$ All Pos- itions, Scatter Cor- rected, %
1C1LT	-0.269	-0.291	-0.242	-0.257	-0.279	-0.241	-0.259
1C2LT	-0.260	-0.328	-0.271	-0.254	-0.327	-0.281	-0.287
1C3LT	-0.303	-0.373	-0.294	-0.296	-0.370	-0.316	-0.327
1C4LT		-0.605		-0.555*	-0.600	-0.555*	-0.570
1C5LT	-0.533	-0.596	-0.491	-0.522	-0.586	-0.505	-0.538
1C6LT	-0.579	-0.650	-0.530	-0.595	-0.672	-0.540	-0.602
1C7LT	-0.584	-0.571	-0.570	-0.586	-0.585	-0.593	-0.588
1H4LT	+0.023	+0.079	+0.022	+0.033	+0.086	+0.006	+0.042
1H5LT	+0.048	-0.012	-0.005	+0.060	+0.001	-0.016	+0.015
1H7LT	+0.007	-0.061	-0.003	-0.005	-0.075	-0.026	-0.003

* Estimated

TABLE IXCHANGE IN SHEAR VELOCITY FOR IRRADIATED A302-B, FROM MIDDLE OF PLATE

Specimen Identi- fication	$\Delta V_S/V_S$ Position 1-4 %	$\Delta V_S/V_S$ Position 2-5 %	$\Delta V_S/V_S$ Position 3-6 %	$\Delta V_S/V_S$ Position 1-4 Scatter Cor- rected, %	$\Delta V_S/V_S$ Position 2-5 Scatter Cor- rected, %	$\Delta V_S/V_S$ Position 3-6 Scatter Cor- rected, %	Average $\Delta V_S/V_S$ All Pos- itions, Scatter Cor- rected, %
1C1LM	-0.271	-0.193	-0.338	-0.327	-0.285	-0.421	-0.344
1C2LM	-0.361	-0.413	-0.355	-0.401	-0.494	-0.415	-0.437
1C3LM	-0.300	-0.374	-0.321	-0.285	-0.372	-0.317	-0.325
1C4LM		-0.639		-0.607*	-0.634	-0.590*	-0.610
1C5LM	-0.534	-0.579	-0.556	-0.523	-0.570	-0.560	-0.551
1C6LM	-0.712	-0.667	-0.798	-0.705	-0.708	-0.810	-0.741
1C7LM	-0.519	-0.479	-0.536	-0.511	-0.535	-0.521	-0.522
1H4LM	-0.040	-0.038	-0.182	-0.028	-0.031	-0.183	-0.081
1H5LM	-0.090	-0.076	-0.135	-0.080	-0.065	-0.142	-0.096
1H7LM	-0.137	+0.002	-0.128	-0.129	-0.054	-0.113	-0.099

* Estimated

TABLE X

CHANGE IN SHEAR VELOCITY FOR IRRADIATED A542-B

Specimen Identi- fication	$\Delta V_S/V_S$	$\Delta V_S/V_S$	$\Delta V_S/V_S$	$\Delta V_S/V_S$	$\Delta V_S/V_S$	$\Delta V_S/V_S$	Average
	Position 1-4 %	Position 2-5 %	Position 3-6 %	Position 1-4 Scatter Cor- rected, %	Position 2-5 Scatter Cor- rected, %	Position 3-6 Scatter Cor- rected, %	$\Delta V_S/V_S$ All Pos- itions, Scatter Cor- rected, %
2C1LT	-0.139	-0.242	-0.155	-0.078	-0.187	-0.096	-0.120
2C2LT	-0.223	-0.282	-0.257	-0.158	-0.224	-0.194	-0.192
2C3LT	-0.361	-0.446	-0.422	-0.314	-0.393	-0.324	-0.344
2C4LT	-0.594			-0.558	-0.650*	-0.560*	-0.589
2C5LT	-0.540	-0.648	-0.528	-0.493	-0.596	-0.483	-0.524
2C6LT	-0.536	-0.681	-0.599	-0.547	-0.706	-0.623	-0.625
2C7LT	-0.549	-0.642	-0.543	-0.543	-0.654	-0.545	-0.581
2H4LT	+0.060	-0.031	+0.091	+0.101	+0.018	+0.136	+0.085
2H5LT	+0.045	-0.070	+0.053	+0.097	-0.015	+0.094	+0.058
2H5LT3	-0.093	-0.297	-0.123	-0.070	-0.265	-0.093	-0.143
2H4LT2	+0.051	-0.026	+0.042	+0.091	+0.019	+0.087	+0.066
2H7LT	-0.144	-0.180	-0.146	-0.138	-0.168	-0.148	-0.151

* Estimated

- . 1LM family, highest averaged positive $\Delta V_S/V_S$ is 1X1LM, +0.131%
 highest averaged negative $\Delta V_S/V_S$ is 1X3LM, -0.007%
 Scatter band width = $0.131 - (-0.007) = 0.138\%$
- . 2LT family, highest averaged positive $\Delta V_S/V_S$ is 2A0LT, +0.038%
 highest averaged negative $\Delta V_S/V_S$ is 2X2LT, -0.065%
 Scatter band width = $0.038 - (-0.065) = 0.103\%$

Since each $\Delta V_S/V_S$ data point, representing a position on an irradiated specimen, has been corrected according to the $\Delta V_S/V_S$ of its unirradiated neighbors in the original donor plate the figures used for determining scatter band width are modified to determine positive and negative limits. The number used to modify scatter band width to determine limits is found by averaging the $\Delta V_S/V_S$ readings for all three positions on all unirradiated control specimens, for each family, and subtracting this number from the scatter band width numbers.

- . 1LT family: average of all $\Delta V_S/V_S$ readings = 0.010%;
 limits become: $+0.018 - (-0.010) = +0.028\%$
 $-0.073 - (-0.010) = -0.063\%$
- . 1LM family: average of all $\Delta V_S/V_S$ readings = +0.034%;
 limits become: $+0.131 - (+0.034) = +0.097\%$
 $-0.007 - (+0.034) = -0.041\%$
- . 2LT family: average of all $\Delta V_S/V_S$ readings = -0.037%;
 limits become: $+0.038 - (-0.037) = +0.075\%$
 $-0.065 - (-0.037) = -0.028\%$

Error

It is beyond the scope of this paper to exhaustively determine error.

A reasonable estimate, however, is arrived at as follows:

- . Error due to micrometer measurements was estimated through repetitive remote measurements on each of many specimens including unirradiated control specimens. Reproducibility accuracy was found to be about ± 0.0001 inch. Some additional error is possibly introduced because of unseen burrs on the irradiated specimens. A small correction figure was given all irradiated specimens to account for possible burrs; a somewhat larger correction figure was given irradiated specimens most apt to have been scratched during de-encapsulation. Error from micrometer measurements is estimated to be $\pm 0.0001 / 0.3940 = \pm 0.025\%$.
- . Error due to drift in the electronics, changes in water temperature, human error in reading the oscilloscope, etc., was found through repeated measurements to be about ± 0.03 microsecond, maximum. Since the final data point is the result of averaging many measurements, error is also averaged and is estimated to be $\pm 0.03 \times 10^{-6} / 3 / 44.25 \times 10^{-6} = \pm 0.023\%$.
- . Error related to the ultrasonic method was estimated by comparisons of a) travel times of the various reverberations, b) travel times of the same reverberation but taken when the initial pulse is incident on a different side, and c) travel times of the same reverberation but taken when at various positions of crystals-specimens misalignment. Error due to

ultrasonic method is estimated to be about ± 0.02 microsecond or $\pm 0.045\%$. Total error is considered to be the sum of the individual errors or $\pm 0.025 \pm 0.023 \pm 0.045 = \pm 0.093 \cong \pm 0.1\%$.

Measurement of Change in Longitudinal Velocity, ΔV_L

Ultrasonic Method

A suitable method for making measurements of changes in longitudinal velocity is to measure, in both test specimen and reference standard, the transit time of an echo after it has reverberated back and forth between parallel faces for a preselected number of times; and then convert the difference in transit times to a change in velocity after making appropriate corrections for dimensional differences. After experiments with two or three other methods, the aforementioned method was selected as being the most reliable as well as fairly simple to conduct. See Figure 31 for an illustration of the set-up for ΔV_L measurement.

The reference specimens used for $\Delta V_L/V_L$ measurements were the same specimens used as reference for control specimens' measurements, critical angle method measurements, and, after cross-referencing, $\Delta V_S/V_S$ measurements (the "UO" specimens).

A photo of wave forms of the received echoes in a typical test specimen is shown in Figure 32. Unfortunately, the reverberations rapidly become distorted and one is forced to use an early echo from which to base ΔV_L measurements. Much of the distortion was found to be caused by interference echoes as a result of mode conversions and echoes off the sides parallel to the main propagation path.

FIGURE 31
Method of Transducer Set-up for Measuring Longitudinal
Velocity Changes in Irradiated and Unirradiated Specimens

Interference Pulses

Surface
Echo

Fourth
Reverberation

Time Base = 2 Microseconds/Large Division

FIGURE 32
Longitudinal-Wave-Pulse Reverberations from Traveling
Within Test Specimens

As in the shear wave velocity measurement method, the surface reflection becomes the reference point, in time, for measurements to the selected reverberation; for ΔV_L , the fourth reverberation was selected.

Electronics

A delayed sweep oscilloscope was used for making measurements of changes in elapsed time. See Figure 29 for a block diagram of the measuring circuits. The delaying sweep was triggered by the gated surface echo. Time base of the delaying sweep was set so the main sweep begins at about the same time the desired reverberation arrives (about 13.5 microseconds). Time base of the main sweep was set at 0.05 microseconds per centimeter which results in a resolution of 0.01 microsecond per small graticule division. Center frequency of the received pulse is about 4.2 MHz.

A series of echoes waveforms photographs for the fourth reverberation appears in Figure 33. Time base is 0.05 microsec/cm. Reference is made, for all specimens, to specimen 1UOLM shown in upper left and also in lower right photos. As an example, displacement of the waveform for 1C6LM, is about 0.062 microseconds to the right relative to 1UOLM. Note similarity in shape of waveforms indicating little change in attenuation at 4.2 MHz.

Data Reduction

Tables XI, XII, and XIII show tabulations of the calculated changes in longitudinal velocity for the three families of irradiated specimens. The change in longitudinal velocity, $\Delta V_L/V_L$, is found by converting the measured change in elapsed time, ΔT_L , to a percentage $\Delta T_L/T_L \times 100\%$,

Top: 1U0LM
Bottom: 1C1LM

Top: 1C6LM
Bottom: 1C7LM

Top: 1C2LM
Bottom: 1C3LM

Top: 1H4LM
Bottom: 1H5LM

Top: 1C4LM
Bottom: 1C5LM

Top: 1U0LM
Bottom: 1H7LM

Time Base = 0.05 Microsecond/Large Division Fourth Reverberation all Specimens

FIGURE 33
Longitudinal-Wave Waveforms: Irradiated Specimens Relative
to Unirradiated Specimen

TABLE XI

CHANGE IN LONGITUDINAL VELOCITY
FOR IRRADIATED A302-B, FROM TOP OF PLATE

Specimen Identi- fication	Change In Longitudinal Velocity, $\Delta V_L/V_L$ *						Average $\Delta V_L/V_L$ All Pos. Scatter Corrected -(-0.010), %
	Posit- ion 1, %	Posit- ion 2, %	Posit- ion 3, %	Posit- ion 4, %	Posit- ion 5, %	Posit- ion 6, %	
1C1LT	-0.089	-0.147	-0.140	-0.108	-0.094	-0.092	-0.102
1C2LT	-0.150	-0.165	-0.157	-0.163	-0.175	-0.124	-0.146
1C3LT	-0.209	-0.235	-0.188	-0.229	-0.197	-0.195	-0.199
1C4LT	-0.373	-0.378	-0.374	-0.378	-0.345	-0.334	-0.354
1C5LT	-0.276	-0.327	-0.309	-0.303	-0.339	-0.256	-0.292
1C6LT	-0.321	-0.370	-0.355	-0.385	-0.341	-0.353	-0.344
1C7LT	-0.297	-0.226	-0.279	-0.269	-0.206	-0.218	-0.239
1H4LT	+0.005	+0.009	+0.009	+0.057	+0.024	+0.057	+0.037
1H5LT	-0.052	-0.036	+0.037	-0.081	-0.032	-0.001	-0.018
1H7LT	-0.072	-0.035	-0.006	-0.035	+0.045	-0.010	-0.009

* Measurements taken at six positions; see Figure 26

TABLE XII
CHANGE IN LONGITUDINAL VELOCITY
FOR IRRADIATED A302-B, FROM MIDDLE OF PLATE

Specimen Identi- fication	Change In Longitudinal Velocity, $\Delta V_L/V_L^*$						Average $\Delta V_L/V_L$ All Pos. Scatter Corrected - (+0.033), %
	Posit- ion 1, %	Posit- ion 2, %	Posit- ion 3, %	Posit- ion 4, %	Posit- ion 5, %	Posit- ion 6, %	
1C1LM	-0.152	-0.124	-0.117	-0.151	-0.107	-0.146	-0.166
1C2LM	-0.225	-0.218	-0.148	-0.246	-0.214	-0.158	-0.234
1C3LM	-0.160	-0.175	-0.108	-0.213	-0.165	-0.118	-0.190
1C4LM	-0.368	-0.383	-0.349	-0.405	-0.364	-0.356	-0.404
1C5LM	-0.296	-0.307	-0.312	-0.270	-0.331	-0.313	-0.338
1C6LM	-0.406	-0.424	-0.484	-0.416	-0.357	-0.374	-0.443
1C7LM	-0.273	-0.247	-0.305	-0.356	-0.222	-0.281	-0.314
1H4LM	0	-0.040	+0.013	+0.012	-0.001	+0.028	-0.031
1H5LM	-0.020	-0.034	+0.015	-0.026	-0.004	-0.015	-0.047
1H7LM	-0.048	+0.003	+0.073	+0.005	+0.015	+0.035	-0.019

* Measurements taken at six positions; see Figure 26

TABLE XIII
CHANGE IN LONGITUDINAL VELOCITY
FOR IRRADIATED A542-B

Specimen Identi- fication	Change In Longitudinal Velocity, $\Delta V_L/V_L$ *						Average $\Delta V_L/V_L$ All Pos. Scatter Corrected -(-0.004), %
	Posit- ion 1, %	Posit- ion 2, %	Posit- ion 3, %	Posit- ion 4, %	Posit- ion 5, %	Posit- ion 6, %	
2C1LT	-0.149	-0.043	-0.101	-0.048	-0.099	-0.102	-0.086
2C2LT	-0.120	-0.050	-0.161	-0.082	-0.139	-0.074	-0.100
2C3LT	-0.181	-0.192	-0.248	-0.185	-0.250	-0.245	-0.213
2C4LT	-0.347	-0.306	-0.359	-0.340	-0.349	-0.318	-0.332
2C5LT	-0.315	-0.271	-0.287	-0.261	-0.299	-0.299	-0.285
2C6LT	-0.324	-0.277	-0.357	-0.270	-0.392	-0.328	-0.321
2C7LT	-0.303	-0.199	-0.258	-0.304	-0.264	-0.190	-0.249
2H4LT	-0.025	+0.066	+0.052	+0.039	0	+0.086	+0.040
2H4LT2	-0.013	+0.118	+0.012	+0.062	+0.055	+0.006	+0.044
2H5LT	-0.008	+0.025	-0.037	+0.031	-0.030	-0.012	-0.001
2H5LT3	-0.064	-0.001	-0.072	-0.007	-0.028	-0.053	-0.034
2H7LT	-0.088	+0.021	-0.055	-0.034	+0.002	-0.085	-0.036

* Measurements taken at six positions; see Figure 26

and then subtracting from this the percentage dimensional variation between test specimen and reference specimen at the particular position of interest. This procedure was repeated at six positions (see Figure 26) for each specimen, and the average of the six readings taken as the data point for that specimen.

The final data point used for each specimen, and plotted in the curves in Figures 5, 6, and 7, is the average $\Delta V_L/V_L$ of six positions which has been corrected for scatter.

Scatter Corrections

Again, as was true for shear velocity measurements, additional measurements and calculations were necessary in an effort to reduce scatter since pre-irradiation measurements had not been taken. Changes in longitudinal velocity in the control specimens appeared to be more random, with respect to position in donor plate, than were changes in shear velocity. Primarily for this reason, no corrections were made to irradiated specimens by extrapolating from measurements on their unirradiated neighbors in the original donor plate.

Instead of making individual corrections based on position in the original donor plate, a constant correction figure was given each of the irradiated specimens in each material family. The correction figure was determined by making six $\Delta V_L/V_L$ measurements on each control specimen, using the "U0" specimen as reference (see Figure 26), and then finding the arithmetical mean of all these $\Delta V_L/V_L$ measurements from all the control specimens in the family. Listings of scatter measurements for each material family are found in Tables V, VI, and VII. The correction figures are as follows:

- . A302-B, top of plate (1LT family), $-0.0096\% \cong -0.010\%$
- . A302-B, middle of plate (1LM family), $+0.0327\% \cong +0.033\%$
- . A542-B (2LT family), $-0.0041\% \cong -0.004\%$

A negative sign, in the 1LT family for example, means that the average V_L of all the control specimens was less than that of the reference specimen, 1U0LT, and that a figure of about -0.010% should be subtracted from each of the $\Delta V_L/V_L$ figures measured on irradiated specimens. With the same reasoning, a figure of $+0.033\%$ should be subtracted from the $\Delta V_L/V_L$ data of the 1LM family and -0.004% from the 2LT family data.

Scatter Band Width

Scatter band limits are, for each family, the maximum averaged positive $\Delta V_L/V_L$ and the maximum averaged negative $\Delta V_L/V_L$ for unirradiated specimens, when measured with respect to the family's "U0" reference specimen, and then shifted with the correction figures listed above. These limits are:

- . 1LT family, 1X2LT, $\Delta V_L/V_L = +0.010 - (-0.010) = +0.020\%$
 1LT3, $\Delta V_L/V_L = -0.032 - (-0.010) = -0.022\%$
- . 1LM family, 1X1LM, $\Delta V_L/V_L = +0.129 - (+0.033) = +0.096\%$
 1X3LM, $\Delta V_L/V_L = -0.003 - (+0.033) = -0.036\%$
- . 2LT family, 2A0LT, $\Delta V_L/V_L = +0.040 - (-0.004) = +0.044\%$
 2LT1, $\Delta V_L/V_L = -0.032 - (-0.004) = -0.028\%$

Scatter is shown in Figures 5, 6, and 7 as a variation in position for the unirradiated reference. For example, the unirradiated reference

line in Figure 5, for the 1LT family, could reasonably be anywhere within the region marked scatter, i.e., 0.020% in the negative direction to 0.022% in the positive direction. The most likely position of the unirradiated reference, is however, as shown at $\Delta V_L / V_L = 0$.

Error

Error was estimated on the same basis as was error for the shear velocity measurements. A reasonable estimate is as follows:

- . micrometer measurement error, $\pm 0.025\%$
- . error due to electronic drift, etc., ± 0.005 microsecond = $\pm 0.037\%$
- . error due to ultrasonic method, ± 0.01 microsecond = $\pm 0.074\%$
- . total error is about $\pm 0.025 \pm 0.037 \pm 0.074 = \pm 0.136\%$

Error is greater than for shear velocity measurements because longitudinal measurements were taken about a pulse whose typical transit time was about 13.5 microseconds compared to about 44.25 microseconds for shear measurements.

Measurement of Change in Critical Angle Signal Amplitude, ΔA_{CA}

With minor adjustments, the same immersion test facility used for ΔV_S and ΔV_L measurements can be used for measurements of change in critical angle signal amplitude, ΔA_{CA} .

The critical angle method has been shown to be capable of detecting very small changes in the elastic properties of materials.^(5,47,48,49) Although the basic conditions necessary for the critical angle method are described in the literature,^(50,51) a complete theoretical model covering the many possible parameters has not yet been developed. Accordingly, a

simplified model based partly on theory, partly on experimental observations, and partly on conjecture will be described.

Ultrasonic Method

Two bases for the critical angle method derive from:

1. A very rapid negative (lagging) phase shift, ϕ , of reflected energy relative to incident energy takes place over a very narrow range of incident angles around the Rayleigh critical angle, θ_R .

$$\sin \theta_R = \frac{V_{\text{water}}}{V_{R\text{steel}}}, \text{ where } V_{\text{water}} = \text{velocity of sound in water, and } V_{R\text{steel}} = \text{Rayleigh (surface wave) velocity in steel.}$$

See Figure 34 for a typical plot in 304 steel. At 5 MHz, phase angle ϕ will change from about -113° at incident angle $\theta_i = 30.6^\circ$, to $\phi = -180^\circ$ at $\theta_i = \theta_R \approx 30.84^\circ$, and to $\phi = -250^\circ$ at $\theta_i \approx 31.1^\circ$.⁽⁵²⁾ Thus over $\Delta\theta_i \approx 0.5^\circ$, $|\Delta\phi| \approx 137^\circ$.

2. At the critical angle, i.e., $\theta_R \approx 30.84^\circ$, and for a narrow angular range, i.e., where phase shift changes linearly with the sine of the incident angle, a lateral shift, Δ , parallel to the boundary surface and in the direction of propagation, will take place before the wave reflects as shown in Figure 35. The amount of displacement, Δ , can be defined in terms of wavelength, densities of water and steel, and the appropriate velocities in water and steel.⁽⁵⁰⁾ The amount of displacement has been defined only for a two dimensional theoretical situation where the incident beam is a bounded beam but yet where the wave front approaches a plane wave front; i.e., the energy outside the previously described

FIGURE 34

Phase Shift of Reflected Waves at Water - Stainless Steel Interface, Relative to Incident Waves, at 5MHz

$$\Delta = \frac{2\lambda \rho_1}{\pi \rho} \left\{ \left[\frac{a(a-b)}{b(b-1)} \right]^{1/2} \left[\frac{1 + 6b^2(1-c) - 2b(3-2c)}{b-c} \right] \right\} = \text{Beam Displacement}$$

where

ρ = Water Density

ρ_1 = Steel Density

λ = Wavelength in Water

$a = (V_s/V_w)^2$

$b = (V_s/V_R)^2$

$c = (V_s/V_L)^2$

where

V_s = Shear Wave Velocity in Steel

V_R = Rayleigh Wave Velocity in Steel

V_L = Longitudinal Wave Velocity in Steel

V_w = Velocity in Water

FIGURE 35

Lateral Displacement of Bounded Beam Incident on Water Steel Interface near Rayleigh Critical Angle

narrow angular range, at which $\phi = -K \sin \theta_i$, approaches zero.

Displacement Δ , under the theoretical conditions, will be in the order of 20λ for steel at 5 MHz where λ = wavelength in water ≈ 0.0117 inch.

Certainly the ideal theoretical conditions are not duplicated during the measurements reported herein. The crystals used have a small ratio of crystal diameter to wavelength and consequently a large angle of beam spread will be present. The shape of the crystals' beam lobes are not known to be symmetrical. A three dimensional energy distribution must be considered rather than two dimensional. These and other differences make the experimental conditions different from the theoretical conditions so that the lateral displacement Δ is no longer defined. Both bases (1) and (2), earlier described, have been qualitatively observed, however; and it is the interaction of the laterally displaced waves with the waves, which are essentially not laterally displaced but yet which experience phase shifts from about 0° to about -360° , that enables the critical angle method to be a test for changes in elastic properties.

If a transmit crystal is aligned at the approximate Rayleigh critical angle ($\theta_i = \theta_R$) on an unirradiated reference specimen and if a receive crystal is positioned such that, as time approaches steady-state relative to the start of an ultrasonic beam, the sum of all the ray components incident on the crystal face at 90° will approach zero, then an approximate null will have been established. Time is made to approach steady-state by pulsing a packet of many oscillations--perhaps 30 to 50 oscillations. The central region of the pulse, i.e., after ten or twelve oscillations,

will have approached steady-state and a null will appear as in part A of Figure 36. If a specimen with changed elastic properties replaces the reference specimen, the balance or null becomes disturbed due to a phase and amplitude re-distribution of all the waves reflected from the test specimen and incident on the receive crystal as shown in part B of Figure 36. The amplitude and phase of the central part of the reflected wave is determined by the amount of change to the elastic properties. If the elastic properties had changed about the same amount but in the opposite direction, then the amplitude of the central part of the reflected wave would be about the same but the phase would be different by an angle approaching 180° as shown in part C.

In addition to the re-distribution of phase and magnitude as a result of changes in velocities in the test specimens, additional re-distributions occur because of changes in specimen density and attenuation, and water velocity and density. Since water temperature has a bearing on all these parameters, it was found necessary to maintain a constant temperature throughout the measurements period. Temperature fluctuation effects were avoided by taking measurements over a short period of time and also by loading specimens with care so that the water was not stirred up. Thermostatically controlled water coolers and water heaters were also used from time to time.

In the preceding discussion related to Figure 36, the original reference specimen could well have been an unirradiated specimen. As such, then either increased or decreased velocities showed up as a change in amplitude and the phase insensitive equipment used in this study would be

FIGURE 36
Changes in Ultrasonic Critical Angle Signal Caused by Changes in Elastic Properties

unable to determine any differences. To avoid a necessity for waveform interpretation to determine phase shift, the reference specimen for all measurements was selected as the H4 member of each family. The H4 members were shown, from velocity measurements, to have some likelihood for increased velocities relative to the unirradiated specimens. Thus when the null balance was first established on the H4 specimens, then all subsequent specimens, irradiated or unirradiated, would be expected to show changes in one direction only--the decreasing velocity direction. Corrections were subsequently made to re-reference all specimens of each family to their respective unirradiated "U0" specimen by subtracting the critical angle signal amplitude, obtained on the U0 specimens, from the signal amplitude obtained on each of all specimens in each family thus making the U0 specimen the zero reference.

Electronics

Early measurements, at about 3.2 MHz, were based on a time integration of all the partial signal amplitudes while scanning over a one inch length of each of two sides. A block diagram of the electronics is shown in Figure 37. These measurements, however, were subject to some non-linearities in the electronics. Accordingly, measurements were retaken; on each stationary specimen, four measurements were taken in the center position, one on each side. A block diagram of the electronics is shown in Figure 38. A measurement consisted of measuring RF voltage amplitude, at about 3.8 MHz, in the center portion of the received packet of oscillations. An example of waveforms on a family of specimens is shown

FIGURE 37
Block Diagram of Electronics used for Ultrasonic Critical Angle Method, Time Integrated Scans

FIGURE 38
Block Diagram of Electronics used for Ultrasonic Critical Angle Method, RF Amplitude Measurements

in Figure 39 where time base is 4 microsecond/cm and sensitivity is 1 volt/cm; measurements were taken on the A542-B family in the middle position (position 2) on side 1 (see Figure 26).

Data Reduction

Measurements on all specimens are tabulated in Tables XIV, XV, and XVI. A positive number denotes an increase in amplitude, and a negative number denotes a decrease in amplitude relative to the "U0" reference.

No corrections are necessary for dimensional changes due to swelling since the critical angle measurements are affected only by a small region at and close to the surface. Depth of penetration has been found to be about half way between wave lengths of a longitudinal and a shear wave.⁽⁴⁷⁾

The final data point for each specimen is the weighted average of the normalized averages of several integrated scans and several RF amplitude measurements. Despite some non-linearities in the electronics used in obtaining the integrated scan data points, the method was nevertheless felt to be more accurate than the RF measurements since scatter would be more apt to cause error in RF measurements than in the integrated scans. Accordingly, more weight was given the integrated scans than to the RF measurements in determining the final, weighted average data points used for the curves in Figures 8, 9, and 10.

Scatter Corrections

No corrections were made to the critical angle signal amplitude measurements. Measurements taken on the unirradiated control specimens (Tables V, VI, and VII) did not reveal any pronounced patterns with respect to position in the donor plates; nor was the averaged scatter, of any

FIGURE 39
Critical Angle RF Signals on A542-B Family of Irradiated
Specimens and Unirradiated Specimen 2U0LT

TABLE XIV

CHANGE IN CRITICAL ANGLE SIGNAL AMPLITUDE IN IRRADIATED A302-B (FROM TOP OF PLATE)

Specimen Identi- fication	Average of Four RF Meas- urements Sides 1,2,3,4, v_1	Average of Two Integra- ted Scans Sides 1&3, v_2	Average of Three RF Meas- urements All on Side 1, v_3	Normal- ized Ave. of Four RF Msmts. ($\times \frac{35.20}{13.88}$), ΔA_1	Normal- ized Ave. of Two Int. Scans ($\times \frac{71.12}{25.96}$), ΔA_2	Normal- ized Ave. of Three RF Msmts. ($\times \frac{35.20}{11.37}$), ΔA_3	Weighted Ave. of $\Delta A_1, \Delta A_2,$ & $\Delta A_3,$ ΔA_{CA}
1C1LT	2.88	3.69	3.20	7.30	10.08	9.92	9.35
1C2LT	5.12	6.70	5.03	13.00	18.40	15.60	16.35
1C3LT	6.15	6.77	6.23	15.60	18.60	19.35	18.04
1C4LT	11.30	11.12	9.70	28.60	30.50	30.00	29.90
1C5LT	12.28	11.37	10.37	31.10	31.20	32.05	31.39
1C6LT	14.15	12.97	11.87	35.85	35.50	36.80	35.91
1C7LT	13.88	12.83	11.37	35.20	35.20	35.20	35.20
1H4LT	- 0.55	- 0.40	- 0.13	- 1.39	- 1.10	- 0.40	- 1.00
1H5LT	- 0.05	1.37	0.87	- 0.13	3.76	2.70	2.52
1H7LT	1.00	1.65	1.20	2.53	4.53	3.71	3.83

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TABLE XV

CHANGE IN CRITICAL ANGLE SIGNAL AMPLITUDE IN IRRADIATED A302-B (FROM MIDDLE OF PLATE)

Specimen Identi- fication	Average of Four RF Meas- urements Sides 1,2,3,4, v_1	Average of Two Integra- ted Scans Sides 1&3, v_2	Average of Three RF Meas- urements Sides 1&3, v_3	Normal- ized Ave. of Four RF Msmts. (x $\frac{31.75}{16.00}$), ΔA_1	Normal- ized Ave. of Two Int. Scans (x $\frac{71.12}{25.96}$), ΔA_2	Normal- ized Ave. of Three RF Msmts. (x $\frac{31.75}{10.52}$), ΔA_3	Weighted Ave. of $\Delta A_1, \Delta A_2$ & ΔA_3 , ΔA_{CA}
1C1LM	3.78	4.64	4.47	7.50	12.26	13.50	11.38
1C2LM	6.92	6.61	5.72	13.72	15.69	17.27	15.59
1C3LM	6.92	6.20	5.67	13.72	15.54	17.10	15.47
1C4LM	13.42	10.86	10.39	26.63	29.75	31.30	29.36
1C5LM	14.08	11.60	10.54	27.90	31.80	31.80	30.82
1C6LM	17.20	14.03	12.14	34.10	38.45	36.60	36.90
1C7LM	16.00	11.58	10.52	31.75	31.75	31.75	31.75
1H4LM	- 2.05	0.04	0	- 4.06	0.11	0	- 0.96
1H5LM	1.02	1.22	1.04	2.02	3.34	3.14	2.96
1H7LM	0.72	1.53	1.37	1.43	4.19	4.13	3.48

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TABLE XVI

CHANGE IN CRITICAL ANGLE SIGNAL AMPLITUDE IN IRRADIATED A542-B

Specimen Identi- fication	Average of Four RF Meas- urements Sides 1,2,3,4, v_1	Average of Two Integra- ted Scans Sides 1&3, v_2	Average of Four Integra- ted Scans Sides 1,2,3,4, v_3	Normal- ized Ave. of Four RF Msmts. (x $\frac{37.40}{15.65}$), ΔA_1	Normal- ized Ave. of Two Int. Scans (x $\frac{71.12}{25.96}$), ΔA_2	Normal- ized Ave. of Four Int. Scans (x $\frac{37.40}{13.80}$), ΔA_3	Weighted Ave. of $\Delta A_1, \Delta A_2$ & ΔA_3 , ΔA_{CA}
2C1LT	2.35	2.97	2.79	5.61	8.20	7.56	7.23
2C2LT	4.88	4.94	4.91	11.68	13.53	13.30	12.95
2C3LT	10.05	8.77	8.66	24.00	24.00	23.46	23.73
2C4LT	13.50	11.70	11.54	32.20	32.04	31.30	31.71
2C5LT	15.08	12.69	12.90	36.00	34.78	35.00	35.20
2C6LT	17.75	14.96	14.98	42.40	41.00	40.60	41.15
2C7LT	15.65	13.65	13.80	37.40	37.40	37.40	37.40
2H4LT	- 0.30	- 0.11	- 1.09	- 0.72	- 0.30	2.96	1.23
2H4LT2	0.20	0.20	0.56	0.48	0.55	1.52	1.02
2H5LT	1.78	2.09	2.94	4.25	5.72	7.96	6.47
2H5LT3	1.92	1.84	3.65	4.58	5.05	9.89	7.35
2H7LT	2.52	2.41	4.19	6.02	6.60	11.37	8.84

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material family relative to their respective "U0" reference specimen, of any significance. Also, the amount of signal amplitude variation (scatter) in the control specimens was not too high relative to changes in most irradiated specimens. Specimens from the middle of the A302-B plate had the most scatter of the low alloy steels.

Scatter Band Width

Scatter limits for each family are determined by the two specimens which have respectively the greatest positive and greatest negative deviations of averaged and normalized RF signal amplitude relative to the reference "U0" specimens. These specimens are as follows where scatter data is obtained from Tables V, VI, and VII:

- . 1LT family: 1LT2, $+0.60 (35.20/13.88) = +1.52$
1LT3, $-0.52 (35.20/13.88) = -1.33$
- . 1LM family: 1LM2, $+1.42 (31.75/16.00) = +2.83$
1LM4, $-0.50 (31.75/16.00) = -0.99$
- . 2LT family: 2NOLT, $+0.67 (37.40/15.65) = +1.61$
2AOLT, $-0.12 (37.40/15.65) = -0.30$

Error

Error was determined by taking multiple measurements on a single specimen over a period of time about equal to that used for taking measurements for a single curve. The same error figure was used for all material families, and which, after normalizing, is ± 2.35 as shown in Figures 8, 9, and 10.

APPENDIX F
CHANGES IN ELASTIC PROPERTIES

General

A determination of the inter-relationships between swelling, change in density, change in elastic properties, and effects on stress wave propagation velocities appears to be too formidable a task for inclusion in this study. Propagation velocities vary inversely with the square root of density in the classical interpretation. Radiation damage, however, creates a disturbed lattice structure which certainly must deviate from the classical sense. For example, some swelling is thought to be caused by greater lattice expansion due to interstitials than lattice contraction caused by vacancies.⁽⁹⁾ Even if interstitials are largely annealed out through migration to sinks or formation of loops, etc., some swelling will remain from the continued presence of vacancies.⁽⁶⁾

The effects of families of interstitials and families of vacancies on elasticity are apparently in opposition, however, the former acting to increase and the latter to decrease moduli.⁽²⁰⁾ Since either or both vacancies and interstitials families can cause a net decrease in density but yet their effects on elastic moduli are in opposition to each other, the density correction involved in determining elastic-moduli-changes from measurements of velocity changes is not well defined. Since velocity measurements in this study indicate decreased moduli (for the low temperature exposed specimens), one gains the impression that either some other opposing effect(s) is(are) occurring simultaneously with the stiffening effect of the interstitials or that the swelling is being caused mostly by defects other than interstitial families.

A possible cause of decreased moduli, particularly at reactor temperatures where interstitials are mobile, is that of an assortment of vacancies, vacancy clusters, vacancy loops, depleted zones, etc. In assessing the affects of reduced-atomic-density zones, it is not clear how to introduce a correction factor based on an observed change in density. Some sample calculations are made, however, based on the classical approach, i.e., the changes in apparent moduli are determined as if the change in density is independent of the radiation damage effects on elastic moduli and thus makes a separate contribution to the change in propagation velocities. In any event, as will be shown in the sample calculations for specimen 1C5LT, the density change contribution is not a major one for low temperature irradiated specimens, but probably is for the high temperature irradiated specimens.

Swelling and Change in Density, $\Delta\rho$

Changes in apparent elastic constants can be calculated if changes in shear and longitudinal wave propagation velocities and on material density can be determined. Accuracy of the calculations in this study are undetermined but probably are not too high because of the high possible error in making each of the ΔV_S , ΔV_L , and $\Delta\rho$ (density) measurements. Furthermore, the elastic properties calculations are based on the material being homogeneous and isotropic which is not known to be true. Nevertheless, some data and calculations will be presented here to enable a "feel" of the approximate changes.

As a first step in determination of elastic property changes, changes in density are determined through micrometer measurements of the dimensional changes while assuming mass remains constant. A tabulation of dimensional changes and the calculated density changes are given in Tables XVII, XVIII, and XIX. Refer to Figure 26 for an illustration of "positions" on the test specimens. Only a few length measurements were taken because of their difficulty and consequent high possible error. The few length measurements taken indicated axial swelling occurred in about the same or slightly higher proportion as did cross-section swelling. The column "corrected average swelling positions 1-6" refers to the average swelling of the six positions after a correction figure of 0.0002 inch was subtracted from the sum of the six post-irradiation position measurements as an allowance for estimated measurement error.

Despite repetitive measurements, measurements on unirradiated specimens, visual examination with a telescope, rounding off on the low side, and including a correction figure, some measurements appear to be on the high side. No further corrections are made, however, as such would be too presumptuous. Correlation between swelling and ΔV_S or ΔV_L is not observable except that, in general, swelling of high temperature exposed specimens is less than that of low temperature exposed specimens.

Change in density is found by assuming $\Delta L/L$, where L is a length dimension, to be the same in all three directions in which case $\Delta \rho/\rho = -3(\Delta L)/L$. It is noted that $\Delta \rho/\rho$ was approximately the same in all three

TABLE XVIISWELLING AND CHANGE IN DENSITY,IRRADIATED A302-B (FROM TOP OF PLATE)

Specimen Identi- fication	Rounded Average Dimension Pos. 1&4, <u>in. x 10⁻³</u>	Rounded Average Dimension Pos. 2&5, <u>in. x 10⁻³</u>	Rounded Average Dimension Pos. 3&6, <u>in. x 10⁻³</u>	Corrected Average Swelling Pos. 1-6, <u>in. x 10⁻³</u>	Change in Density, $\Delta\rho/\rho$, <u>%</u>
1C1LT	394.4	394.3	394.3	0.08	-0.06
1C2LT	394.3	394.2	394.3	0	0
1C3LT	394.3	394.2	394.3	0.02	-0.01
1C4LT	394.5	394.4	394.4	0	0
1C5LT	394.8	394.7	394.9	0.28	-0.21
1C6LT	394.5	394.4	394.4	0.18	-0.14
1C7LT	394.8	394.9	394.8	0.32	-0.24
1H4LT	394.7	394.6	394.6	0.18	-0.14
1H5LT	394.2	394.2	394.3	0	0
1H7LT	394.6	394.7	394.6	0.13	-0.10
1U0LT (Unirradiated)	394.3	394.2	394.3		

TABLE XVIII

SWELLING AND CHANGE IN DENSITY,
IRRADIATED A302-B (FROM MIDDLE OF PLATE)

Specimen Identi- fication	Rounded Average Dimension Pos. 1&4, in. x 10 ⁻³	Rounded Average Dimension Pos. 2&5, in. x 10 ⁻³	Rounded Average Dimension Pos. 3&6, in. x 10 ⁻³	Corrected Average Swelling Pos. 1-6, in. x 10 ⁻³	Change in Density, $\Delta\rho/\rho$, %
1C1LM	394.1	394.2	394.1	0.16	-0.12
1C2LM	394.1	394.1	394.3	0.11	-0.08
1C3LM	394.3	394.3	394.4	0.23	-0.17
1C4LM	394.3	394.3	394.3	0.10	-0.07
1C5LM	394.4	394.3	394.4	0.36	-0.27
1C6LM	394.5	394.5	394.5	0.27	-0.20
1C7LM	394.4	394.5	394.3	0.28	-0.21
1H4LM	394.2	394.0	394.0	0.10	-0.07
1H5LM	394.1	394.1	394.0	0.11	-0.08
1H7LM	394.3	394.3	394.3	0.25	-0.19
1U0LM (Unirradiated)	394.2	394.2	394.3		

TABLE XIXSWELLING AND CHANGE IN DENSITY,IRRADIATED A542-B

Specimen Identi- fication	Rounded Average Dimension Pos. 1&4, in. x 10 ⁻³	Rounded Average Dimension Pos. 2&5, in. x 10 ⁻³	Rounded Average Dimension Pos. 3&6, in. x 10 ⁻³	Corrected Average Swelling Pos. 1-6, in. x 10 ⁻³	Change in Density, $\Delta\rho/\rho$, %
2C1LT	394.2	394.2	394.2	0.08	-0.06
2C2LT	394.3	394.3	394.3	0.20	-0.15
2C3LT	394.5	394.4	394.3	0.30	-0.23
2C4LT	394.2	394.2	394.1	0.13	-0.10
2C5LT	394.3	394.3	394.3	0.33	-0.25
2C6LT	394.5	394.5	394.4	0.45	-0.34
2C7LT	394.4	394.2	394.5	0.31	-0.23
2H4LT	394.2	394.2	394.2	0.10	-0.07
2H4LT2	393.7	393.9	393.8	0.05	-0.04
2H5LT	394.3	394.1	394.1	0.07	-0.05
2H5LT3	394.3	394.3	394.3	0	0
2H7LT	394.3	394.2	394.2	0.05	-0.04
2U0LT (Unirr- adiated)	394.1	394.1	394.1		

families for the C5 series (also the C7 series). Since this similarity indicates improved accuracy of the measurement at these series, one of them, the 1C5LT specimen, will be used as the model for the sample elastic constants calculations to follow. A tabulation of apparent elastic properties changes for 1C1LT, 1C5LT, and 1H4LT specimens is found in Table I.

Sample Calculations of Changes in Elastic Constants

Shear Modulus

Shear modulus is given by $G = \rho V_S^2$, where $G_{\text{steel}} \approx 8.09 \times 10^{11}$ dyne/cm²,
 $\rho_{\text{steel}} \approx 7.8$ gm/cm³,
 and $V_S \approx 3.22 \times 10^5$ cm/sec.

$$\Delta G = V_S^2 \Delta \rho + 2\rho V_S \Delta V_S$$

$$\Delta G/G = \Delta \rho/\rho + 2 \Delta V_S/V_S, \text{ or } \Delta G/G = 0.128 \Delta \rho + 0.621 \times 10^{-5} \Delta V_S$$

for 1C5LT, $\Delta \rho/\rho \approx -0.21\%$ (from Table XVII)

$$\Delta V_S/V_S \approx -0.538\% \text{ (from Table VIII)}$$

$$\Delta G/G \approx -0.210 - 1.076 = -1.286\%$$

$$\Delta \rho \approx -0.0021(7.8) = -0.0164 \text{ gm/cm}^3$$

$$\text{and } \Delta G \approx -0.01286(8.09 \times 10^{11}) = -0.104 \times 10^{11} \text{ dynes/cm}^2$$

Bulk Modulus

Bulk modulus is given by $K = \rho V_L^2 - 4/3 \rho V_S^2$,

$$\text{where } K_{\text{steel}} \approx 16.71 \times 10^{11} \text{ dynes/cm}^2$$

$$\Delta K/K = \Delta \rho/\rho + 2 (V_L \Delta V_L)/(V_L^2 - 4/3 V_S^2) - 8/3 (V_S \Delta V_S)/(V_L^2 - 4/3 V_S^2)$$

for 1C5LT, $\Delta\rho/\rho \approx -0.0021$

$$V_L \approx 5.94 \times 10^5 \text{ cm/sec}$$

$$V_S \approx 3.22 \times 10^5 \text{ cm/sec}$$

$$\Delta V_L \approx -0.00292 (5.94 \times 10^5) = -0.01735 \times 10^5 \text{ cm/sec (from Table XI)}$$

$$\Delta V_S \approx -0.00538 (3.22 \times 10^5) = -0.01733 \times 10^5 \text{ cm/sec}$$

$$\Delta K/K \approx \Delta\rho/\rho + 0.555 \times 10^{-5} \Delta V_L - 0.40 \times 10^{-5} \Delta V_S$$

$$\Delta K/K \approx -0.0021 - 0.00962 + 0.00693 = -0.00479$$

$$\Delta K/K \approx -0.48\% \text{ and } \Delta K \approx -0.0048(16.71 \times 10^{11}) = -0.080 \times 10^{11} \text{ dynes/cm}^2$$

Poisson's Ratio

Poisson's Ratio is given by: $\sigma = \frac{V_L^2 - 2V_S^2}{2(V_L^2 - V_S^2)}$, where $\sigma_{\text{steel}} \approx 0.291$

$$\frac{\Delta\sigma}{\sigma} = \frac{2V_S V_L}{(V_L^2 - 2V_S^2)(V_L^2 - V_S^2)} (V_S \Delta V_L - V_L \Delta V_S)$$

for 1C5LT, $V_L \approx 5.94 \times 10^5 \text{ cm/sec}$

$$V_S \approx 3.22 \times 10^5 \text{ cm/sec}$$

$$\Delta V_L \approx -0.01735 \times 10^5 \text{ cm/sec}$$

$$\Delta V_S \approx -0.01733 \times 10^5 \text{ cm/sec}$$

$$\Delta\sigma/\sigma \approx 0.341 \times 10^{-5} \Delta V_L - 0.629 \times 10^{-5} \Delta V_S$$

$$\Delta\sigma/\sigma \approx -0.0059 + 0.0109 = 0.0050$$

$$\Delta\sigma/\sigma \approx 0.50\% \text{ and } \Delta\sigma \approx 0.005(0.291) = 0.001455$$

Young's Modulus

Young's modulus is given by: $E = \rho V_S^2 \frac{3V_L^2 - 4V_S^2}{V_L^2 - V_S^2}$

where $E_{\text{steel}} = 20.9 \times 10^{11} \text{ dynes/cm}^2$

$$\frac{\Delta E}{E} = \frac{\Delta \rho}{\rho} - \left[\frac{2V_S V_L^2}{(V_L^2 - V_S^2)(3V_L^2 - 4V_S^2)} - \frac{2}{V_S} \right] \Delta V_S + \left[\frac{2V_L V_S^2}{(V_L^2 - V_S^2)(3V_L^2 - 4V_S^2)} \right] \Delta V_L$$

$$\Delta E/E \approx \Delta \rho/\rho + 0.478 \times 10^{-5} \Delta V_S + 0.077 \times 10^{-5} \Delta V_L$$

$$\Delta E/E \approx -0.0021 - 0.00828 - 0.00138 = -0.01176$$

$$\Delta E/E \approx -1.176\% \text{ and } \Delta E \approx -0.01176(20.9 \times 10^{11}) = -0.246 \times 10^{11} \text{ dynes/cm}^2$$

Methods of Determining Radiation Damage Caused Changes in Elastic Properties

Interatomic Potentials Change

Diene's expressions for elastic constants of a body-centered cubic lattice structure may be found in Reference (20). The expressions determine changes in bulk modulus and the two shear moduli as a result of changes in potential energy per atom from changes in interatomic distances due to the presence of interstitials and vacancies. Various simplifying assumptions are made regarding the homogeneity of the damaged medium. Graphical corrections are made for relaxation effects.

Dienes predicts decreases in bulk modulus, both shear moduli, and Young's moduli in the presence of vacancies. He suggests 1% vacancies decreases the bulk modulus about 2.3% and also notes, when using Bruggeman's⁽⁵²⁾ equations (based on elasticity theory), that 1% vacancies decreases the shear modulus about 1.5%;⁽²¹⁾ 1% interstitials increase bulk modulus about 9%; whereas using Bruggeman's equations, the shear modulus is increased about 6.3%.⁽²¹⁾ In the presence of equal numbers of interstitials and vacancies, the decreases as a result of vacancies will be more than canceled out and the net effect will be increases in the moduli.

Dislocations Interactions

The change-in-velocity expression involving dislocation damping and dislocation density is as follows, assuming low strain amplitude:⁽²²⁾

$$V(\omega) = V_0 \left\{ 1 - \left(\frac{8Ga^2}{\pi^3 C} \right) \left(\frac{\Lambda \omega_0^2 L^2}{2\pi} \right) \left[\frac{\omega_0^2 - \omega^2}{(\omega_0^2 - \omega^2) + (\omega B/A)^2} \right] \right\}$$

where $V(\omega)$ = alternating stress wave velocity at angular frequency, ω

V_0 = velocity at resonant frequency, ω_0 , of dislocations

G = the appropriate elastic modulus

a = the Burger's vector

A , B , and C = constants from the differential equation of a vibrating dislocation loop length

Λ = dislocation density

L = dislocation loop length

if $\omega/\omega_0 \ll 1$, and ignoring effects of all other mechanisms except those of dislocation density and dislocation damping, the above expression can be reduced to

$$\Delta V/V = K_2 L^2 \Lambda \quad \text{where } \Delta V/V = \frac{V_0 - V(\omega)}{V_0} \quad \text{and}$$

K_2 = a constant

Thus, at a frequency $\omega \ll \omega_0$, a decrease in dislocation loop length will cause an increase in $V(\omega)$. An increase in dislocation density will cause a decrease in $V(\omega)$. If dislocation loop length does not decrease indefinitely with increasing neutron fluence but instead rapidly saturates at some fraction of the pre-irradiation loop length, say $1/3$;⁽³⁰⁾ but if dislocation density continues to increase along with fluence, say from $2 \times 10^8/\text{cm}^3$ to $3 \times 10^{10}/\text{cm}^3$ at 5 to 8×10^{19} nvt > 1 Mev,⁽³¹⁾ an increase of

150X, then the net effect, becoming more dominant as exposure increases, could be a decrease in $V(\omega)$. Under this over-simplified relationship, propagation velocities would show an initial increase and then, while still at low fluences, would reverse direction; as fluence increases, the magnitude of the decrease would ultimately exceed that of the increase so that net change would be a decrease.

Porosity, Classical Mechanics

Mackenzies expressions for elastic constants of a solid containing spherical holes are as follows:⁽³²⁾

Bulk Modulus, K

$$\frac{1}{K} = \frac{1}{K_0 \rho_r} + \frac{3}{4\mu_0} \frac{1 - \rho_r}{\rho_r} (1 + c\sigma^2)$$

where K = bulk modulus of medium with holes

K_0 = bulk modulus of medium without holes

μ_0 = shear modulus of medium without holes

$\sigma \cong 0$ (refers to the standard deviation of the volumes of the holes)

ρ_r = (density of material with holes/density of material without holes)

$$c = 5 \frac{3K_0 + 4\mu_0}{9K_0 + 8\mu_0} \cong 2, \text{ (for metals)}$$

Shear Modulus, μ

$$\frac{\mu_0 - \mu}{\mu_0} = 5 \frac{3K_0 + 4\mu_0}{9K_0 + 8\mu_0} (1 - \rho_r)$$

where μ = shear modulus of medium with holes

Bradfield has re-expressed the above relationships as follows:⁽³³⁾

$$\Delta K/K = - (1 - \rho_r) \frac{3}{2} \left(\frac{1 - \sigma}{1 - 2\sigma} \right)$$

$$\Delta G/G = - (1 - \rho_r) \frac{15(1 - \sigma)}{7 - 5\sigma}$$

$$\Delta E/E = - (1 - \rho_r) \frac{3(9 + 5\sigma)(1 - \sigma)}{2(7 - 5\sigma)}$$

where $\Delta K = K - K_0$, $G = \mu_0$, $\Delta G = \mu - \mu_0$,

E = Young's modulus without holes, and $\Delta E = E - E_0$ where

E_0 = Young's modulus with holes

Using Bradfield's expressions and assuming $\rho_r = 0.9979/1.00$ and

$\sigma = 0.291$ (Poisson's ratio for steel),

$$\Delta K/K \approx -0.00533 \approx -0.53\%$$

$$\Delta G/G \approx -0.00403 \approx -0.40\%$$

$$\Delta E/E \approx -0.00421 \approx -0.42\%$$

thus indicating a decrease in all three moduli in the presence of spherical holes (examples are for a 0.21% decrease in density).

Also using Bradfield's expressions and assuming $\rho_r = 0.9979/1.00$, apparent shear velocity = true shear wave velocity x 0.99904, and apparent longitudinal velocity = true longitudinal wave velocity x 0.99864, thus indicating a decrease in both shear and longitudinal velocities in the presence of spherical holes. Note that longitudinal velocity decreases more than does shear velocity. Also, the prediction of decreased longitudinal velocity is in opposition to the predictions from the following section involving an expression for spherical cavity scatterers.

Multiple Scatterers

Spherical Elastic Scatterers

The change-in-velocity expression for spherical elastic scatterers⁽³⁵⁾ involves Lamé's elastic constants which assumes an isotropic medium. The materials used for this study would only approximately meet this requirement.

Truell's expression for change in compressional-wave velocity

is:

$$\frac{v - v'}{v'} = 1/2 \frac{\Delta\tau}{\tau} \left[\frac{\rho_2}{\rho_1} - \frac{\lambda_1 + 2\mu_1}{\lambda_2 + 2\mu_2 - 4/3(\mu_2 - \mu_1)} + \frac{10(\mu_2 - \mu_1)}{2(\mu_2 - \mu_1) + 3(\mu_2/\mu_1 + 3/2)(\lambda_1 + 2\mu_1)} \right]$$

where v = compressional wave velocity with no scatterers

v' = compressional wave velocity with multiple elastic scatterers

$\Delta\tau/\tau$ = volume fraction of scatterers present

ρ_2 = density of scatterers

ρ_1 = density of matrix

λ_2, μ_2 = Lamé's Constants for scatterers

λ_1, μ_1 = Lamé's Constants for matrix

where $\lambda = \rho(V_L^2 - 2V_S^2)$ and $\mu = \rho V_S^2$

It is assumed that interstitials families will cause a greater increase in elastic constants than in density due to the exponential nature of interatomic forces on elastic moduli contrasted to a linear relationship between density and number of atoms per unit volume. Thus for an assumption of $\rho_2/\rho_1 \approx 1.10$, assume $\mu_2/\mu_1 \approx 1.15$ and $\lambda_2/\lambda_1 \approx 1.20$. Using the assumed values for μ_2 and λ_2 where $\lambda_1 = 11.3 \times 10^{11}$ dynes/cm², and $\mu_1 = 8.1 \times 10^{11}$ dynes/cm²; and neglecting the third term within the large brackets, the second term within the brackets is found to be approximately equal to 0.90 so that $(v - v')/v' = 0.1 \Delta\tau/\tau$, a positive number.

Multiple interstitial scattering centers, accordingly, would appear to cause a decrease in compressional (longitudinal) velocity.

It should be noted, however, that although Truell measured longitudinal velocity increases⁽³⁵⁾ in neutron irradiated silicon, he also measured shear velocity decreases⁽³⁶⁾ indicating a decrease in C_{44} , or μ , (shear modulus) and an increase in C_{11} , or $\lambda + 2\mu$. If μ decreased but $\lambda + 2\mu$ increased, then the magnitude of $\Delta\lambda$ must exceed the magnitude of $2\Delta\mu$.

Spherical Cavity Scatterers

The change-in-velocity expression for spherical cavity scatterers again makes the assumption of an isotropic medium.⁽³⁵⁾

$$\frac{v - v'}{v'} = 9/2 \frac{\Delta\tau/\tau}{\left[\frac{7}{9} - \frac{7}{12} (K_1/k_1)^2 + \frac{3}{16} (K_1/k_1)^4 \right] \left[1 - 9/4 (K_1/k_1)^2 \right]}$$

where v and $\Delta\tau/\tau$ are as defined under Spherical Elastic Scatterers.

v' = compressional wave velocity with multiple spherical cavity scatterers, and $K_1/k_1 = V_L/V_S \approx \frac{5.94 \times 10^5 \text{ cm/sec}}{3.22 \times 10^5 \text{ cm/sec}} = 1.845$ for steel.

The term within the large brackets is found to be approximately equal to -0.73 and $(v - v')/v' = -3.3 \Delta\tau/\tau$. Multiple vacancy scattering centers, accordingly, would appear to cause an increase in longitudinal velocity.

The magnitude of changes in the spherical elastic and spherical cavity scatterer sample calculations are not expected to be accurate although they are apparently compatible with Truell's statement that cavities are the strongest scatterer.⁽³⁵⁾

The expressions for change in shear velocity as a function of multiple elastic or multiple cavity scatterers are not available at the time of this writing. As noted earlier, however, shear velocity decreases and longitudinal velocity increases were measured in the same neutron

irradiated silicon material.^(35,36) Furthermore, direction of velocity changes are expected to be frequency or scatterer size dependent.⁽⁵³⁾

The findings on a single silicon crystal do not necessarily apply to polycrystalline BCC metal alloys. A basis for comparison might be found, however, in the trends of changes. For example, the total differentials of bulk modulus $K = \lambda + 2\mu/3$ is $C_1 \Delta K = 0.67 \Delta\mu + \Delta\lambda$,

of shear modulus $G = \mu$ is $\Delta G = \Delta\mu$,

of Young's modulus $E = \frac{\mu(3\lambda+2\mu)}{\lambda+\mu}$ is $C_2 \Delta E = 13.3 \Delta\mu + \Delta\lambda$,

and of Poisson's Ratio $\sigma = \frac{\lambda}{2(\lambda+\mu)}$ is $C_3 \Delta\sigma = -1.4 \Delta\mu + \Delta\lambda$

where C_1 , C_2 , and C_3 are constants.

For a decrease in μ and an increase in λ , it would not be unreasonable to expect decreases in E and G with either a smaller decrease or an increase in K . This finding is in line with Truett's observation of decreased μ and increased $\lambda+2\mu$ and also with data reported in this paper (Table I) where apparent changes in K were in the same direction as but considerably less than changes in G and E (for low temperature exposed specimens).

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