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# FINAL REPORT

on

# EXAMINATION, TESTING AND EVALUATION OF IRRADIATED PRESSURE VESSEL SURVEILLANCE SPECIMENS FROM THE VERMONT YANKEE NUCLEAR POWER STATION

to

YANKEE ATOMIC ELECTRIC COMPANY

May 15, 1984

by

L. M. Lowry, M. P. Failey, M. P. Landow,
D. Stahl, R. G. Jung, and R. S. Denning

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# LEGAL NOTICE

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## 1.0 SUMMARY

A 30-degree azimuthal surveillance capsule assembly was received from the Vermont Yankee Reactor. The capsule was visually examined, opened, and the specimens inventoried. The basket contained a complete compliment of eight tensile specimens and 36 Charpy specimens.

The 30-degree Vermont Yankee surveillance capsule marked 117C 4084 G1 was irradiated for 7.54 equivalent full power years (EFPY) and was removed from the reactor after shutdown on March 4, 1983. Three iron, three copper, and three nickel neutron monitor wires from Charpy packets G1, G2, and G3 were

analyzed. The capsule specimens received a fast neutron fluence (E > 1 MeV) of 4.30 x $10^{16}$ n/$cm^2$. The calculated maximum fast neutron fluence at the 1/4 T pressure vessel wall position occurred at about zero degree azimuthal and was 3.78 x $10^{16}$ n/$cm^2$ at the time the capsule was removed from the reactor vessel. The capsule lead factor was 0.83 which indicates that the flux at the capsule slightly lags the flux at certain vessel wall positions. The maximum 1/4 T fast neutron fluence after 32 EFPY of operation was calculated to be 1.61 x $10^{17}$ n/$cm^2$ (assuming a reactor lifetime of 40 years and 80 percent of full power operation at 1593 $MW_t$).

Charpy impact specimens were tested to determine the impact behavior, including the impact energy, lateral expansion, fracture appearance, and upper shelf energies for irradiated base metal, weld metal, and heat affected zone (HAZ) metal. The instrumented Charpy V-notch test results reported include load-time curves, general yield loads, maximum loads, brittle fracture loads, and crack arrest loads for each of the base, weld, and HAZ metal specimens. The base metal exhibited the largest 30 ft-lb shift and therefore is the limiting material for the Vermont Yankee Reactor pressure vessel. The adjusted reference nil-ductility transition temperature ($RT_{NDT}$) was calculated to be 79 F (initial $RT_{NDT}$ of 60 F plus the shift of 19 F) for the base metal at the maximum fast fluence pressure vessel location (0-degree) and at the pressure vessel 1/4 T position at the end of the capsule irradiation time on March 4, 1983. Using Regulatory Guide 1.99, the predicted maximum end of life (EOL) shift in $RT_{NDT}$ (assuming 32 EFPY) was estimated to be at most about 40 F for the Vermont Yankee Reactor pressure vessel base metal for the position of maximum fluence (0-degree) and at the 1/4 T wall position (1.61 x $10^{17}$ n/$cm^2$). The predicted EOL adjusted $RT_{NDT}$, therefore, is about 100 F. The base metal also exhibited the largest drop in upper shelf energy of 20 ft-lb to 128 ft-lb. The predicted EOL upper shelf energy, as estimated from Regulatory Guide 1.99, is not expected to fall below about 90 ft-lb. This is well above the minimum allowable EOL upper shelf energy of 50 ft-lb specified in 10CFR50 Appendix G. The tensile properties of the irradiated specimens were determined, including the yield and ultimate tensile strengths, as well as uniform and total elongations, and reductions in area. The Rockwell B hardness was determined from indents made in three irradiated base metal and three irradiated weld metal specimens using a calibrated hardness tester.

The halves of five broken weld metal Charpy V-notch specimens were analyzed for copper (Cu), nickel (Ni), and phosphorus (P) using the method of X-ray fluorescence. The base metal averaged 0.11 weight percent Cu, 0.68 weight percent Ni, and 0.014 weight percent P while the weld metal averaged 0.030 weight percent Cu, 0.95 weight percent Ni, and 0.013 weight percent P.

## 2.0 INTRODUCTION

Irradiation of materials such as pressure vessel steels used in commercial nuclear power reactors cause changes in the mechanical properties of the material. Specimens such as tensile and Charpy V-notch are used to evaluate radiation-induced changes in the material tensile, impact, and fracture properties.(1-6)* Tensile properties generally exhibit a decrease in uniform elongation, total elongation, and reduction-in-area accompanied by an increase in yield and ultimate tensile strength with increasing neutron exposure. The impact properties as determined by Charpy V-notch impact tests generally exhibit an increase in the ductile-to-brittle transition temperature and a drop in the upper shelf in energy.

The Vermont Yankee Reactor is a boiling water reactor (BWR) designed by the General Electric Company (GE). The reactor pressure vessel receives neutron irradiation during operation and as a result is subject to radiation-induced embrittlement. Because the reactor pressure vessel contains the reactor core and coolant, the changes in fracture properties must be known. Therefore, a pressure vessel surveillance program is required by the U.S. Nuclear Regulatory Commission (NRC) and material surveillance capsules containing appropriate specimens are placed into each commercial nuclear power reactor prior to initial startup. The purpose of the surveillance program associated with each reactor is to monitor the changes in mechanical properties as a function of neutron exposure.

The Vermont Yankee Generating Plant has a surveillance program which is described in reports issued by the General Electric Company.(7, 16) The program is based on ASTM E185 "Standard Practice for Conducting Surveillance Tests for Light-Water Cooled Nuclear Power Reactor Vessels",(8) and was conducted using numerous other American Society for Testing and Materials (ASTM) and American Society of Mechanical Engineers (ASME) standards.(9-15)

Three surveillance capsules, each containing Charpy and tensile mechanical property test specimens and iron (Fe), copper (Cu), and nickel (Ni)

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* References are listed at the end of the text.

dosimeter wires, were inserted into the reactor pressure vessel prior to the initial startup of the Vermont Yankee Nuclear Reactor. Figure 1 shows the position of the three (30, 120, and 300-degree) capsules.

The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Appendix G for Nuclear Power Plant Components, Division 1 presents a procedure for obtaining allowable loading for ferritic pressure retaining materials to protect against nonductile failure. The procedure is based on the principles of linear elastic fracture mechanics and is related to the reference nil ductility transition temperature ($RT_{NDT}$).

The Code of Federal Regulations(13) requires that reactor vessels for which the predicted values of the adjusted $RT_{NDT}$ (initial $RT_{NDT}$ plus shifts due to irradiation) exceeds 200 F or the Charpy V-notch upper shelf energy is below 50 ft-lb at end of life, must be designed to permit a thermal annealing treatment at a sufficiently high temperature to recover material toughness properties of ferritic materials of the reactor vessel beltline. $RT_{NDT}$ is defined in reference 14, and is the higher of the nil-ductility transition temperature ($T_{NDT}$) determined by drop weight tests(15) and the Charpy V-notch test temperature ($T_{CV}$) minus 60 F. $T_{CV}$ must not exceed $T_{NDT}$ + 60 F and be that temperature at which three Charpy V-notch specimens exhibit not less than 50 ft-lb absorbed energy and at least 35 mils lateral expansion. Thus the reference temperature $RT_{NDT}$ is the higher of $T_{NDT}$ and $T_{CV}$ - 60 F. Tests of base metal, weld metal, and HAZ metal Charpy V-notch specimens must be conducted and the highest $RT_{NDT}$ used to calculate the reference mode I stress intensity factor $K_{IR}$. Startup and operation curves are generated based on the calculated $K_{IR}$. At the time of initial operation of the reactor, the pressure-temperature operating curves were specified. During the life of the reactor, the curves are to be revised to account for the changes in the Charpy impact behavior of the pressure vessel material due to irradiation. The adjusted pressure-temperature operating curves then allow for safe hydrostatic pressure testing, startup, and operation of the reactor.

A previous report covers the preirradiation baseline tensile and Charpy impact properties of the three materials from the Vermont Yankee Reactor.(32) These materials include base metal, weld metal, and heat-affected-zone (HAZ) metal. The present report includes descriptions of the recovery and disassembly of the Vermont Yankee 30-degree surveillance capsule

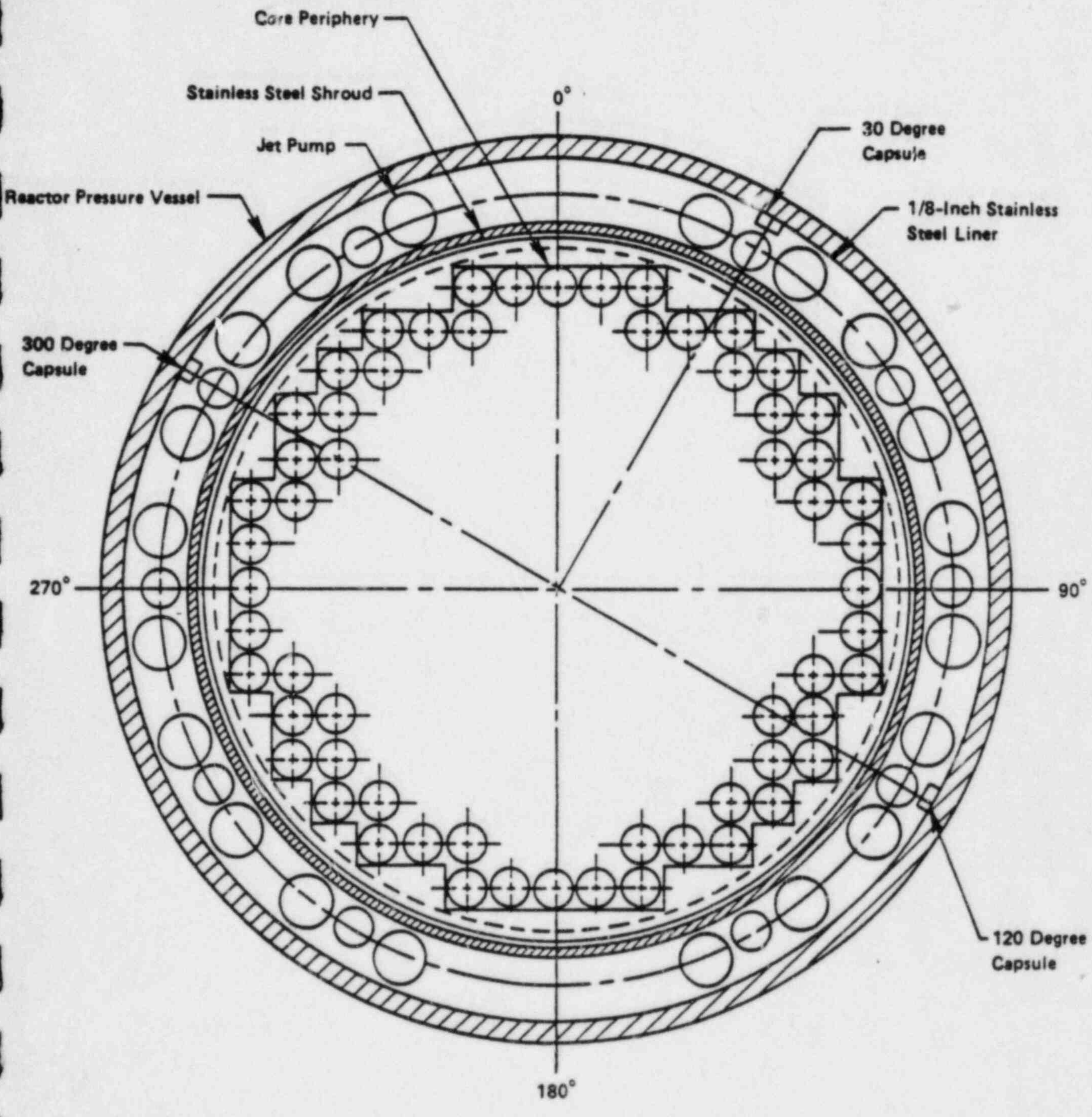


FIGURE 1. VERMONT YANKEE CORE MIDPLANE SHOWING THE LOCATION OF THE 30-DEGREE, 120-DEGREE, AND 300-DEGREE SURVEILLANCE CAPSULES

and the examination of the test specimens and dosimetry wires. This report also includes the procedures and results of the tensile, hardness, and Charpy impact tests and dosimetry and chemical analysis for the Vermont Yankee 30-degree surveillance capsule which was removed from the reactor during March of 1983.

The BCL surveillance capsule quality assurance program is a planning, controlling, surveillance, and documentation program to assure that all work is conducted following the basic principles of scientific investigation. The organization of this program follows the requirements of Title 10 CFR Part 50 Appendix B, ASME NA-4000, and ASME Section III NB-2360, "Calibration of Instruments and Equipment", where applicable to testing verification. All tests were conducted in full compliance with the Nuclear Materials Technology Quality Assurance Manual. This manual is responsive to all 18 criteria of a quality assurance program.

Implementation of the quality assurance requirements included the use of technical and quality assurance authorized work instructions, procedures, and work completion forms. The forms were used to document that all data was generated in compliance with the procedures and conformed to requirements of the applicable ASTM specifications. Both Charpy and tensile machines were periodically certified to ensure accurate and reliable results. A system of technical overchecks and independent quality assurance surveillance was used to insure compliance with the procedures and the overall quality assurance program. All personnel were trained and certified in compliance with ANSI N45.2.6 as being technically qualified for the task being undertaken and were aware of the quality assurance requirements.

All data-generating instruments and apparatus were calibrated by standards traceable to the U.S. Bureau of Standards.

Specimen receipt and the packaging and shipment of wastes for disposal are in accordance with the quality assurance program which is reponsive to Title 10 CFR Part 71, Appendix E. All waste material from the capsules was disposed of in containers authorized by the applicable Department of Transportation (DOT) and Nuclear Regulatory Commission (NRC) regulations at a properly licensed waste disposal site. Mechanical property specimens are being held for 6 months following receipt of the final technical report by Yankee Atomic Electric Company.

## 3.0 SPECIMEN PREPARATION

The base metal for the Vermont Yankee reactor pressure vessel is A533 Grade B Class 1 steel. Charpy V-notch and tensile specimens were prepared from an actual beltline plate (No. 2 shell and piece marked 1-14). The specimens were prepared from A533 steel plate (Heat No. C3017-2) provided by Lukens Steel Corporation in 1969. Base metal specimens were taken from flat slabs cut parallel to both the plate surfaces at a depth of one-quarter and three-quarter plate thickness. The Charpy and tensile base metal specimens were machined with their longitudinal axes parallel to the plate rolling direction and the Charpy specimen notches were cut perpendicular to the plate surface. Both Charpy and tensile base metal specimens were designated longitudinal specimens.

The weld metal for the Vermont Yankee Reactor pressure vessel was made according to Chicago Bridge and Iron Company Weld Procedure WPS-1 and welded using the shielded metal arc process. The Charpy weld metal specimens were machined in a direction transverse to the weld direction; thus, only the central notched section of the specimen would necessarily be composed of weld-deposited metal. Charpy specimens were taken throughout the weld section to a depth of 1-1/16 inch from the weld root. The Charpy weld metal specimens' long axes were therefore parallel to the plate surface, and the notches were cut perpendicular to the plate surface. The tensile weld metal specimens were composed entirely of weld metal and were obtained by machining the specimens parallel to the weld length and parallel to the plate surface.

The Charpy HAZ metal specimens were machined in a direction transverse to the weld length and parallel to the plate surface. The axes of the notches were then cut perpendicular to the plate surface, with the notch located at the intersection of the base metal and weld deposit. The tensile HAZ metal specimens were machined transverse to the weld length and parallel to the plate surface. The joint between the base metal and weld deposit was located at the center of the tensile specimen gage length.

A modification of a marking system developed by the U.S. Steel Corporation's Applied Research Laboratory (designated FAB Code) was used to mark one end of each surveillance Charpy and tensile specimen for later positive identification.

A typical Charpy V-notch impact specimen is shown in Figure 2 and is a standard specimen design recommended in ASTM E23-82 entitled "Standard Methods for Notched Bar Impact Testing of Metallic Materials". The typical tensile specimen design shown in Figure 3 conforms to recommendations in ASTM E8-81 for subsize specimens. The ASTM E8-81 standard is entitled "Standard Methods for Tension Testing of Metallic Materials".

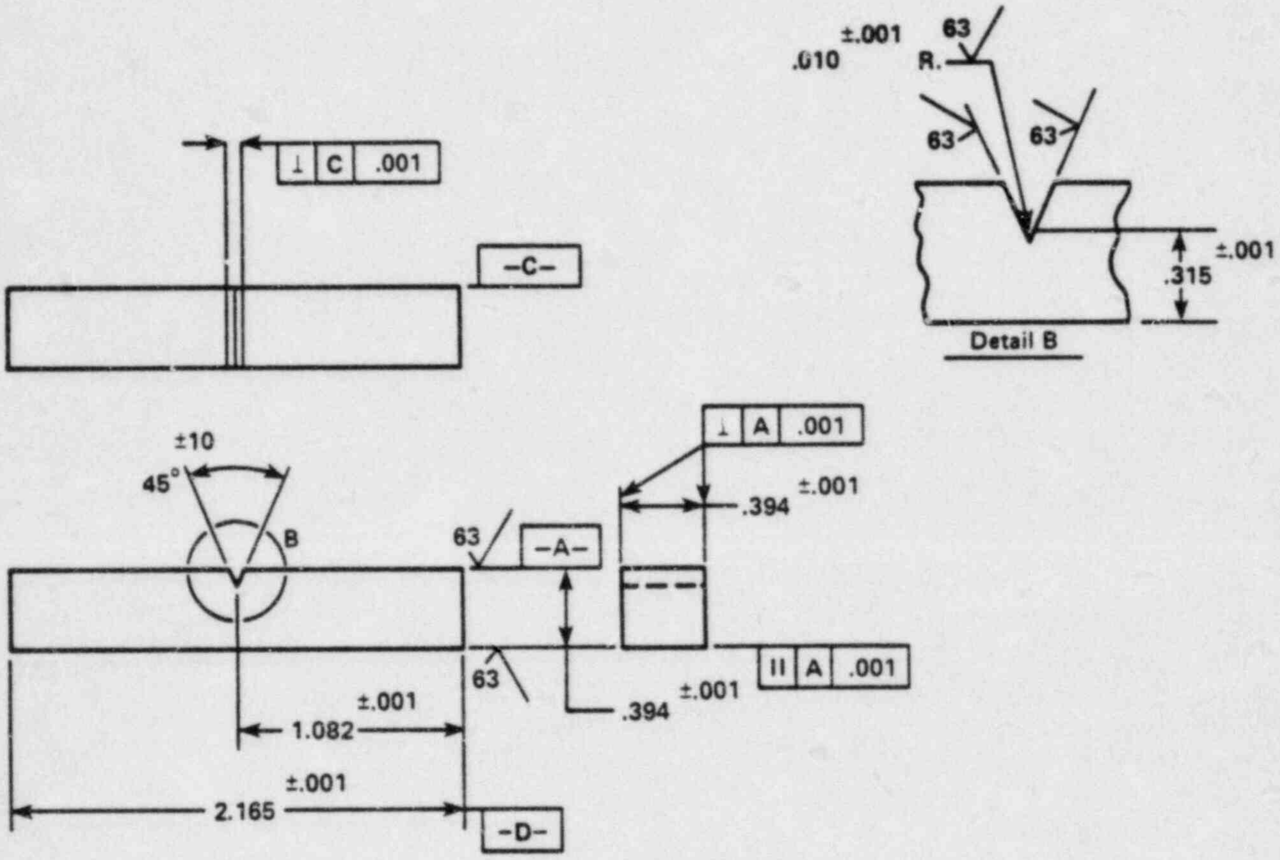
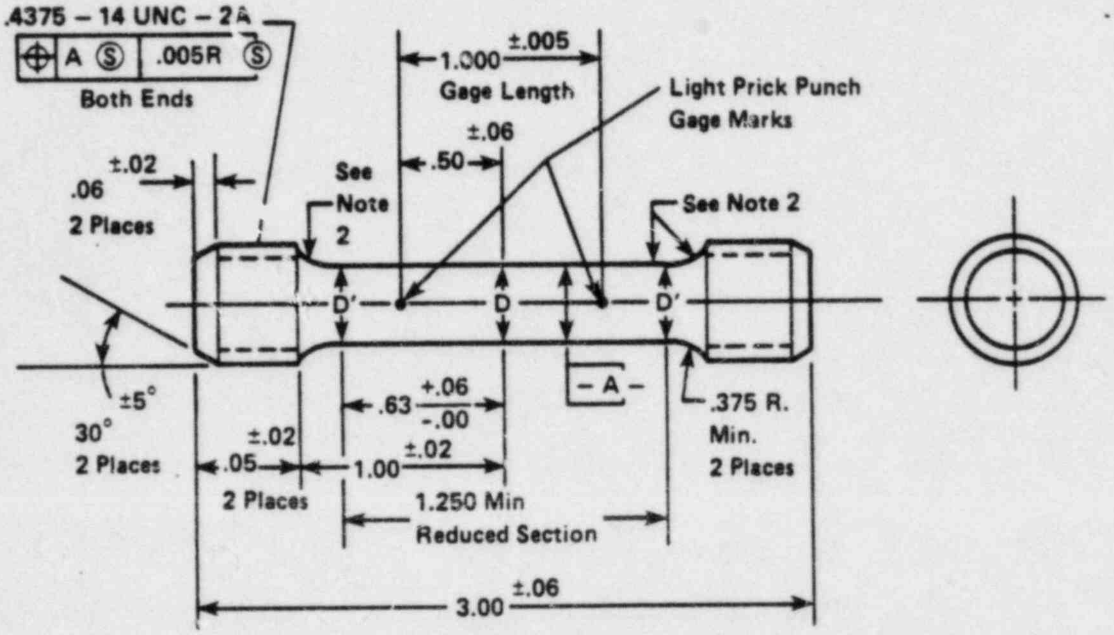


FIGURE 2. TYPICAL CHARPY V-NOTCH IMPACT SPECIMEN



Notes:

1. $D = .250^{\pm .001}$ dia. at center of reduced section. D' = actual D dia. + .002 to .005 at ends of reduced section tapering to D at center.
2. Grind reduced section and radii to 32✓ radii to be tangent to reduced section with no circular tool marks at point of tangency or within reduced section. Point of tangency shall not lie within reduced section.

FIGURE 3. TYPICAL TENSILE SPECIMEN

## 4.0 CAPSULE RECOVERY AND DISASSEMBLY

The surveillance capsule assembly was shipped from the Vermont Yankee Reactor site to the Battelle Columbus Laboratories (BCL) hot laboratory for postirradiation examination. Upon arrival at BCL on June 8, 1983, the assembly was transferred to a hot cell for visual examination, serial number verification, photography, and disassembly.

The initial visual examination revealed no notable features. Two views of the capsule basket are shown in Figure 4. From these photographs, it appeared that the basked contained the expected four tensile tubes and three Charpy packets. The basket bore the serial number 117C 4084 G1. The baskets bore the Vermont Yankee Reactor code number 24 and the basket code number 1, which correspnds to the applicable group number, and is the same as the last digit in the basket serial number. The Vermont Yankee Reactor code number and basket code number appear as a binary code, as explained in Reference 7. The binary code numbers (drilled holes) appeared in the lower corners of the basket surface facing the pressure vessel wall (back face) and the serial number (stamped alphanumeric) appeared in the lower center of the basket surface facing the core (front face). (See Figure 4). The binary code identified this basket as coming from the 30-degree orientation.

The basket was opened by cutting away the lower (spacer packed) end using a flexible abrasive cut-off wheel attached to a Mototool*. The basket did contain four intact tensile tubes and three Charpy packets. Identification numbers of the tubes and packets are listed below in the order of their location with the first being located at the top of upper basket and the last being located at the bottom of the upper basket. The Charpy packets had both the binary code numbers and the alphanumeric identification, whereas the tensile tubes contained only a letter and a number stamped into one end of the plug.

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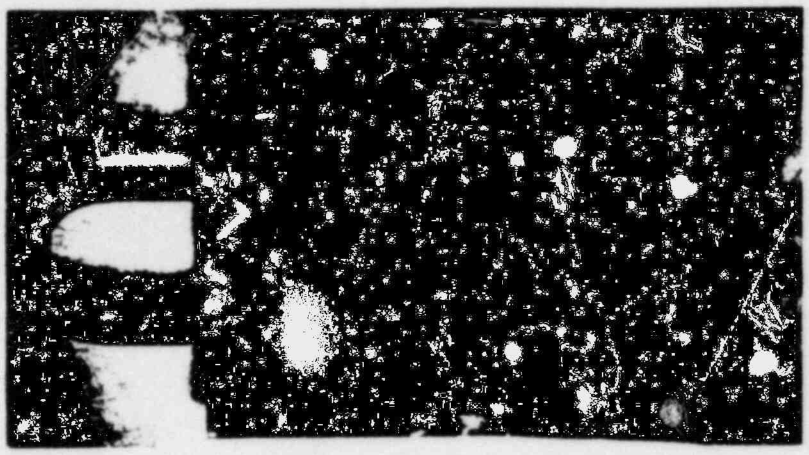
* Mototool is a trademark for a variable, high-speed motor attached to a flexible shaft and chuck for grinding and cutting operations.



0.3X A1117, A1118

CAPSULE BACK SIDE*

0.3X A1115, A1116

CAPSULE FRONT SIDE*

*The capsule front side was facing the core and back side was facing the pressure vessel wall.

FIGURE 4. VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

| | | |
|---|---|---|
| Tensile Tube | | G1 |
| Tensile Tube | | G3 |
| Charpy Packet | 117C 4083 | G1 |
| Tensile Tube | | G4 |
| Tensile Tube | | G5 |
| Charpy Packet | 117C 4083 | G2 |
| Charpy Packet | 117C 4083 | G3 |

The three Charpy packets were also opened using the abrasive cut-off wheel to remove one end of the packet. The basket faces were separated slightly with the fingers of the manipulator. The specimens were then removed by tilting the packet and allowing the specimens to drop out the open end. Each Charpy packet contained one iron (Fe), one copper (Cu), and one nickel (Ni) dosimeter wire. An inventory of the Charpy specimens is given in Table 1, and a total of 12 base metal, 12 weld metal, and 12 HAZ metal specimens were recovered.

The four tensile tubes were opened using the abrasive cut-off wheel to remove one end of the tube. The specimens were then removed by shaking the tube and allowing the specimens to drop out the open end. An inventory of the tensile specimens is also given in Table 1, and a total of three base metal, two weld metal, and three HAZ metal specimens were recovered.

A photograph of a typical Charpy packet is shown in Figure 5. Similarly, a photograph of a typical tensile tube is shown in Figure 6.

TABLE 1. INVENTORY OF CHARPY AND TENSILE SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE BASKET ("FAB" CODE)

| Charpy Packets | | |
|---|---|---|
| G1(a) | G2(b) | G3(c) |
| JC5 | JJM | JPC |
| JBJ | JE5 | JP4 |
| JDJ | JKP | JPB |
| JB3 | JJT | JLD |
| JBK | JEU | JP2 |
| JB1 | JKE | JM6 |
| JBB | JKM | JLT |
| JCA | JJ7 | JP3 |
| JCC | JJB | JMD |
| JBD | JJL | JL7 |
| JBT | JEC | JP6 |
| JD1 | JJ3 | JPA |

| Tensile Tubes | | | |
|---|---|---|---|
| G1(a) | G3(c) | G4 | G5 |
| JTJ | JY3 | JTU(a) | JU6(b) |
| JT3 | JYJ | JUJ(b) | JY6(c) |

(a) Base metal specimens.
(b) Weld metal specimens.
(c) HAZ metal specimens.

FIGURE 5. TYPICAL CHARPY PACKET FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

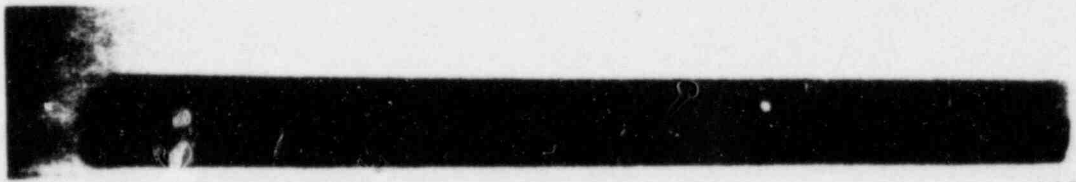


FIGURE 6. TYPICAL TENSILE TUBE FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

## 5.0 EXPERIMENTAL PROCEDURES

This section of the report describes the general procedures used to determine the neutron ( 0.1 and 1.0 MeV) flux and fluence and to determine the pressure vessel material impact and tensile properties. The general procedures for chemical analysis are also included. All tests were performed at Battelle's Columbus Laboratories (BCL). All data evaluations were performed at BCL and the original data are recorded in Laboratory Record Book 38815.

### 5.1 Neutron Dosimetry

The Vermont Yankee surveillance basket contained three Charpy specimen packets. The flux monitor wires, one each of iron (Fe), copper (Cu), and nickel (Ni), were recovered from inside each of the Charpy packets. Each wire was identified, placed in a plastic vial, brought out of cell, ultrasonically cleaned in a water/soap solution, placed in a clean vial, and transferred to the radiochemistry area for further cleaning and analysis. The wires were cleaned by wiping using successive swabs containing dilute acid (10 volume percent nitric for Cu and Ni and 25 volume percent hydrochloric for Fe), distilled water, and reagent alcohol until a negligible contamination level was reached. The dosimeter wires were counted and wire data was generated.

Depending on the wire activity, a suitable and representative sample was selected for counting. Dosimeter wires from Charpy packets G1, G2, and G3 were weighted to an accuracy of ± 0.0001 g using a calibrated (NBS traceable) analytical balance. The wires were then mounted and analyzed by gamma ray spectroscopy. Fast neutron flux and fluence values with energies greater than 0.1 MeV and greater than 1.0 MeV at the capsule wall, 1/4 T, and 3/4 T locations were calculated. Data used in these determinations included the following:

| Dosimeter Material | Reaction | Threshold Energy, MeV | Half-Life |
|---|---|---|---|
| Fe, pure | $^{54}$Fe (n, p) $^{54}$Mn | 2.5 | 312.6 days |
| Cu, high purity | $^{63}$Cu (n, $\alpha$) $^{60}$Co | 6.1 | 5.27 years |
| Ni | $^{58}$Ni (n, p) $^{58}$Co | 2.1 | 71.2 days |

The ASTM procedures followed in the measurement of the monitor activities and calculation of the neutron flux included:

ASTM E261-77, "Measuring Neutron Flux, Fluence, and Spectra by Radioactivation Techniques"

ASTM E263-82, "Determining Fast-Neutron Flux Density by Radioactivation of Iron"

ASTM E264-77, "Determining Fast-Neutron Flux by Radioactivation of Nickel"

ASTM E522-78 "Calibration of Germanium Detectors for Measurement of Gamma-Ray Emission Rates of Radionuclides"

ASTM E523-76, "Measuring Fast-Neutron Flux Density by Radioactivation of Copper"

ASTM E482-76, "Application of Neutron Transport Methods for Reactor Vessel Surveillance".

The BCL premium, high resolution 50 cc high-purity germanium detector, capable of 2.0 KeV resolution (full width, half maximum at $^{60}$Co 1332 KeV peak) was calibrated with NBS standard reference materials and was used to determine the radioactivity induced in the flux wires. Data handling and reduction were accomplished using an Ortec Model 7010 Multichannel Analyzer (4096 channels).

The integrated neutron fluence at the surveillance location was determined from the radioactivity induced in the irradiated detector materials. The gamma radiation from the dosimeter was measured and used to calculate the flux required to produce this level of activity. The fluence was then calculated from the integrated power output of the reactor during the exposure interval.

The activity A induced into an element irradiated for a time $t_i$ in a constant neutron flux is given by:

$$A = N[\int_0^\infty \sigma(E)\phi(E)dE](1 - e^{-\lambda t_i})$$

where

$\sigma(E)$ = the differential cross section for the activation reaction (barns)

$\phi(E)$ = the neutron differential flux ($n/cm^2/sec$)

N = the atom density of the target nuclei (atoms/g)

$\lambda$ = the decay constant of the product atom ($sec^{-1}$).

If the sample is permitted to decay for a time $t_w$ between exposure and counting, then the activity when counted is:

$$A = N[\int_0^\infty \sigma(E)\phi(E)dE](1-e^{-\lambda t_i})\ e^{-\lambda t_w} .$$

If it is desired to find the flux of neutrons with energies above a given energy level, $E_c$, the cross section corresponding to this energy level is defined as:

$$\sigma(E>E_c) = \frac{\int_0^\infty \sigma(E)\phi(E)dE}{\int_{E_c}^\infty \phi(E)dE}$$

where

$$\phi(E>Ec) = \int_{E_c}^\infty \phi(E)dE$$

Then

$$\int_0^\infty \sigma(E)\,\phi\,dE = \frac{\int_0^\infty \sigma(E)\,\phi\,(E)dE}{\int_{E_c}^\infty \phi(E)dE} \int_{E_c}^\infty \phi(E)dE$$

$$= \sigma(E>E_c)\,\phi\,(E>E_c)$$

and the activity A may be written as:

$$A = N\,\sigma(E>E_c)\,\phi(E>E_c)\,(1 - e^{-\lambda t_i})\,e^{-\lambda t_w} \quad .$$

The flux is then computed from the measured activity as:

$$\phi(E>E_c) = \frac{A}{N\,\sigma(E>E_c)\,(1 - e^{-\lambda t_i})\,e^{-\lambda t_w}} \quad .$$

To correct for fluctuations in power level, the flux is computed as:

$$\phi(E>E_c) = \frac{A}{N\,\sigma(E>E_c)C}$$

where

$$C = \sum_{n=1}^{N} f_n\,(1 - e^{-\lambda t_i^n})\,e^{-\lambda t_w^n} \quad .$$

$N$ = number of time intervals of constant flux

$f_n$ = the fractional power level during interval n

$t_i^n$ = the time length of the interval n irradiation

$t_w^n$ = the time between the end of interval n and counting.

In order to determine the effective cross section to be used in the above calculations, the cross section as a function of energy must be known and the neutron flux intensity as a function of energy must be known. A cross section library of this nature is available (18) and a computer code DETAN(19) was used to retrieve the cross sections desired from this library. The neutron flux and spectrum was calculated with computer code DOT.(20) This code solves the two-dimensional Boltzmann transport equation using the method of discrete ordinates. The reactor gemetrical configuration design was modeled to simulate the core structure, intervening structures, and pressure vessel. Calculations were performed in the $S_8P_3$ approximation using 47 neutron group cross sections from the DLC-74 library.(21) The evvective cross sections were generated by the DOT calculation. Coincidental with the calculation of the effective cross sections in the DOT run, the lead factor and neutron flux profile in the reactor vessel wall were also determined.

The neutron fluence was calculated by multiplying the flux (neutrons per square centimeter per second) by the time of operation at full power (using effective full power seconds). To perform the computations, the following information was used:

(1) A description or sketch of the fuel bundle arrangement making up the core, the structures between the core and the pressure vessel, and the pressure vessel itself. This description included materials, thicknesses, and distances between components. The cladding material properties and thickness was also included.

(2) The average fast flux distribution in the core. These data included the fuel bundles in one octant of the core and covered the entire time span during which the capsule was in the reactor.

(3) Detailed capsule and capsule holder drawings and the exact position of the capsule relative to other structures.

(4) A complete energy generation history by month ($MWH_t$ per month) for the time during which the capsule was in the reactor, plus a value considered to be full power.

## 5.2 Charpy Impact Properties

Charpy impact tests were conducted using a 264 ft-lb Tinius-Olsen Model 74 impact machine in accordance with ASTM specifications.(11, 22) The 264 ft-lb range was used for all tests. Velocity of the hammer at impact was 16.87 ft/sec. Calibration of the machine was verified as specified in ASTM E23-82 and proof tested using a set of standard Charpy specimens obtained from the U.S. Army Materials and Mechanics Research Center (AMMRC) of Watertown, Massachusetts. Results of the proof tests are listed in Table 2.

Instrumented impact tests were conducted utilizing a tup (hammer) on the impact machine to which strain gage instrumentation had been added. The instrumented tup in conjunction with a computer controlled, programmable system and a digital storage oscilloscope to record the load-time history of each impact test was used as the data acquisition system.(23) The information stored in the oscilloscope was then recorded using an X-Y plotter to produce hard copies of the test load-time curves. Testing of the irradiated Charpy V-notch specimens from the Vermont Yankee surveillance capsule followed in general the recommendations of the General Electric document SIL No. 14, Supplement 1.

TABLE 2. CALIBRATION DATA FOR THE HOT LABORATORY CHARPY IMPACT MACHINE USING AMMRC STANDARDIZED SPECIMENS

| Energy Group | BCL Energy (ft-lb) (Average of 5 tests) | AMMRC Standard Energy[a] (ft-lb) | Variation Between BCL Average And AMMRC Standard Energy | |
|---|---|---|---|---|
| | | | Actual | Allowed |
| Pretest Low Energy | 14.9 ± 0.4 | 14.6 | -0.3 ft-lb | ±1.0 ft-lb |
| Posttest Low Energy | 14.2 ± 0.5 | 14.6 | -0.4 ft-lb | ± 1.0 ft-lb |
| Pretest High Energy | 70.4 ± 2.3 | 72.5 | -2.9 percent | ± 5.0 percent |
| Posttest High Energy | 70.6 ± 1.0 | 72.5 | -2.6 percent | ± 5.0 percent |

(a) Established by U.S. Army Materials and Mechanics Research Center.

ASTM procedure E23-82 for specimen temperature control was utilized. The low temperature bath consisted of a refrigeration unit containing methyl alcohol. The alcohol was agitated by a magnetic stirring bar to minimize temperature variation in the bath. The liquid level of the bath was maintained so that a minimum of 1 inch of liquid over the specimens was maintained. Each Charpy specimen was held at temperature for at least the minimum time (± 1 C for at least 5 minutes) recommended by ASTM E23-82. Tests above room temperature were conducted in a similar manner using a heated oil bath.

Each specimen was transferred from the temperature bath to the anvil of the impact machine by an automatic transfer device. Specimens were removed from the bath and impacted in less than 5 seconds as the testing proceeded. The energy required to break each specimen was recorded and plotted as a function of test temperature.

Lateral expansion was determined from measurements made with a lateral expansion gage.(22) The amount of lateral expansion as a function of test temperature was also plotted. Fracture appearance (percent shear) of the Charpy specimens was estimated from observation of the fracture surface and by comparing the appearance of the specimen to an ASTM fracture appearance chart.(11)

The Battelle's Columbus Laboratory approach was to test each type specimen (base, weld, and HAZ metal) in the approximate temperature range of -50 F to 400 F with the actual test temperature mutually agreed upon prior to testing. The data generated was used to construct conventional Charpy transition curves, which could then be used to determine the adjusted reference temperature ($RT_{NDT}$). Emphasis was placed on establishing a 30 ft-lb, 50 ft-lb, and 35 mil lateral expansion index temperatures. Because of the current concern regarding the upper shelf energy level of pressure vessel materials, tests were also conducted in a manner such that the upper shelf was well-defined. Items reported include test temperature, energy abosrbed by the specimen in breaking, lateral expansion, percent ductile fracture, upper shelf energy, 30 ft-lb level nil-ductility transition (NDT) temperature, 50 ft-lb level NDT temperature, and photographs of each pair of fracture surfaces. The Charpy impact data was prepared and reported in accordance with ASTM E185-82.(8)

## 5.3 Tensile Properties

Tensile tests were conducted using a screw-driven Instron machine having a 20,000 pound capacity. The tensile properties of base metal, weld metal, and HAZ metal specimens were determined following the procedures of ASTM E8-81,(24) "Tension Testing of Metallic Materials", ASTM A370-77,(11) "Mechanical Testing of Steel Products", and ASTM E21-79,(25) "Elevated Temperature Tension Tests of Metallic Materials". Prior to testing, each tensile specimen diameter was measured using a blade micrometer, and an initial cross-sectional area was calculated for each specimen. The samples of each material were tested at room temperature ( 80 F), 180 F and 543 F. The representative operating temperature of the Vermont Yankee Nuclear Generating Plant was about 550 F. Temperatures of the specimens tested at elevated temperatures were monitored by two Chromel-Alumel thermocouples attached directly to the gage length. As required by ASTM, temperature control was maintained to ± 5 F of the desired test temperature for 20 minutes prior to start of, as well as during, the tensile test. Tensile specimens were heated by means of a hot air-furnace.

The testing machine crosshead speed was 0.005 in./min from the beginning of the test until well past the 0.2 percent offset yield point. The crosshead speed was then increased to 0.05 in./min and held at this speed to the end of the test. A knife edge extensometer was attached directly to the tensile specimen central one inch gage section. A strain gage unit sensed the differential movement between the two extensometer extension arms which were attached to the specimen gage section by two vee-notched knife edge bars. The extension arms are required so that the strain gage can be located outside the furnace hot zone during elevated temperature testing. Elongation of the tensile specimen (at a crosshead speed of 0.005 in./min) was measured to a point beyond the yield point using the strain gage extensometer over a one inch gage section. Once the yield point was passed, the crosshead speed was increased to 0.05 in./min. After the extensometer was switched off, the specimen elongation was determined by multiplying the crosshead speed by the elapse time and dividing by the specimen gage section length (1.0 in.). After testing, each broken tensile specimen was reassembled using a special jig, photographed, and the distance between the punch marks measured. Each specimen was also photographed end-on to show the fracture surface.

Load-elongation data were recorded on the testing machine strip chart. Yield strength, ultimate tensile strength, uniform elongation, and total elongation were determined from these charts. The reduction in area was determined from specimen measurements made using a blade micrometer. Total elongation was also determined from the increase in distance between two punch marks (originally one-inch apart) which were made in the gage section prior to testing.

The Instron load cell was calibrated prior to testing using a strain gage tensile bar which had been calibrated against NBS traceable standards. The Instron crosshead speeds were also determined using a calibrated stop watch and a calibrated dial indicator. The extensometer was also calibrated before tensile testing using an Instron high-magnification drum-type extensometer calibrator. The calibrator was calibrated using NBS traceable standards.

## 5.4 Chemical Analysis

The method of X-ray fluorescence (XRF) was used to determine copper (Cu), phosphorus (P), and nickel (Ni) contents. Each sample consisted of a separate half of a broken weld metal Charpy specimen which was polished through 600 grit grinding paper to provide a satisfactory surface for analysis. Both tantalum and aluminum masks were used to accommodate the sample. The masked-down samples and NBS standards (with known amounts of each element) were bombarded with primary X-rays to produce measurable characteristic or secondary X-rays of the desired elements. These characteristic or secondary X-rays which result from inner orbital electron jumps of a particular element are produced in proportion to the amount of that element in the sample. Qualification and calibration was achieved by comparing the accummulated intensities and wavelengths of the X-rays from the sample to those from NBS standards possessing a known concentration range for each element.

The procedure for the chemical analysis for the elements listed above involved counting on the major lines and at off-line background positions. Counts were accummulated for up to 200 seconds at least twice for each sample to improve counting statistics. Electronic pulse height analysis (PHA) which allows elimination of excessive background due to the radioactivity of the sample was incorporated for the phosphorous, vanadium, silicon, and sulfur analysis. This PHA provided greater sensitivity in the net intensities for elements of low concentration.

The standards used for this analysis are certified NBS standards. They included low alloy steels standards Numbers 1161 through 1169, and cast steel standards Numbers 1104 through 1183.

The XRF procedures used in this program are those in general use throughout the industry and are described in the literature. Two sources that typify common practice are:

(1) Theory and Practice of X-Ray Fluorescence; Philips Electronic Inst., Mt. Vernon, New York.

(2) Principles and Practices of X-Ray Spectrochemical Analysis; E. P. Bertin; Plenum Press (1969).

## 5.5 Hardness Tests

Rockwell hardnesses of the base and weld metal specimens were measured. A series of five indents were made on the side of an untested Charpy V-notch impact specimen such that the indents were in the base or weld metal as required. The measurements were made in accordance with ASTM E18-79, "Standard Tests Method for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Material". The Wilson Model 3YR hardness testing machine was calibrated to ASTM E18-79 specifications just prior to conducting the tests, and five indents were made in a test block of comparable hardness before testing the unirradiated specimens.

# 6.0 RESULTS AND DISCUSSION

## 6.1 Neutron Dosimetry

### Introduction

The neutron environment to which a surveillance capsule has been exposed must be known so that the pressure vessel material property changes (tensile and Charpy V-notch property changes) can be related to that environment. However, the exact neutron spectrum is very complicated and varies over the operating history of the reactor. Therefore, the Vermont Yankee surveillance program utilizes iron, nickel, and copper dosimeter wires to yield an integrated flux at the capsule position. The activation process is both time and energy dependent and a computer code is used to establish the neutron energy spectrum at the capsule position. Once the integrated flux at the capsule has been established, the flux or fluence 0.1 MeV and 1.0 MeV can be calculated at other radial and azimuthal positions within the pressure vessel.

### Analytical Method

The determination of the neutron flux at the capsule, and subsequently in the pressure vessel wall, requires the completion of three procedures. First, the disintegration rate of the product isotope per unit mass of the flux monitor must be determined. This has been discussed earlier under experimental procedures. Second, in order to find a spectrum-averaged reaction cross section at the capsule location, the neutron energy spectrum must be calculated. Third, the neutron flux at the capsule must be found by calculations involving the counting rate data, the spectrum-averaged cross sections, and the operating history of the reactor.

The energy and spatial distribution of neutron flux in the reactor were calculated using the DOT 4.3 computer program.(20) DOT solves the Boltzmann transport equation in two-dimensional geometry using the method of discrete ordinates. Balance equations are solved for the density of particles moving along discrete directions in each cell of a two-dimensional spatial mesh. Anistotropic scattering is treated using a Legendre expansion of arbitrary order.

The two-dimensional geometry that was used to model the Vermont Yankee Reactor is shown in Figure 7. As seen, there are 18 circumferential meshes and 70 radial meshes. Capsule 1 includes circumferential meshes 7, 8 and 9 and radial meshes 60 and 61. Third order scattering was used ($P_3$) and 48 angular directions of neutron travel (24 positive and 24 negative) were used ($S_8$ quadrature). Neutron energies were divided into 47 groups with energies from 17.3 MeV to $10^{-5}$ eV. The 47 group structure is that of the RSIC Data Library DLC75/BUGLE 80(21), and neutron absorption, scattering, and fission cross sections used are those supplied by this library. The core shroud and jet pumps are Type 304 stainless steel. The capsule is also modeled as a solid piece of Type 304 stainless steel. The reactor pressure vessel wall is SA533B steel. The reactor core was mocked up as homogenized fuel and water having the densities found in the operating reactor. The water in the core region has a density consistent with saturation conditions at the operating pressure of 1020 psia and a core-averaged steam volume fraction of 0.294. The water in the downcomer has a density consistent with an inlet subcooling of 27.1 Btu/pound. Finally, the fuel was a source of neutrons having a U-235 fission energy spectrum. The relative power in the assemblies nearest the capsule, during the interval the capsule was in the reactor, is shown in Figure 7.(26) A plane view of the Vermont Yankee Reactor physical geometry at the core midplane is shown in Figure 7 and because of symmetry includes only a 1/8th segment.

The neutron spectrum at the capsule center, as calculated by DOT, is shown in Figure 8. Also shown for comparison is the fission spectrum. The fission spectrum was normalized to contain one neutron above 1.0 MeV. The neutron spectrum at the capsule center was normalized to contain the same flux as the fission spectrum at 1.0 MeV energy. As can be seen, the capsule spectrum is considerably harder than the fission spectrum. This is caused by neutron travel through water.

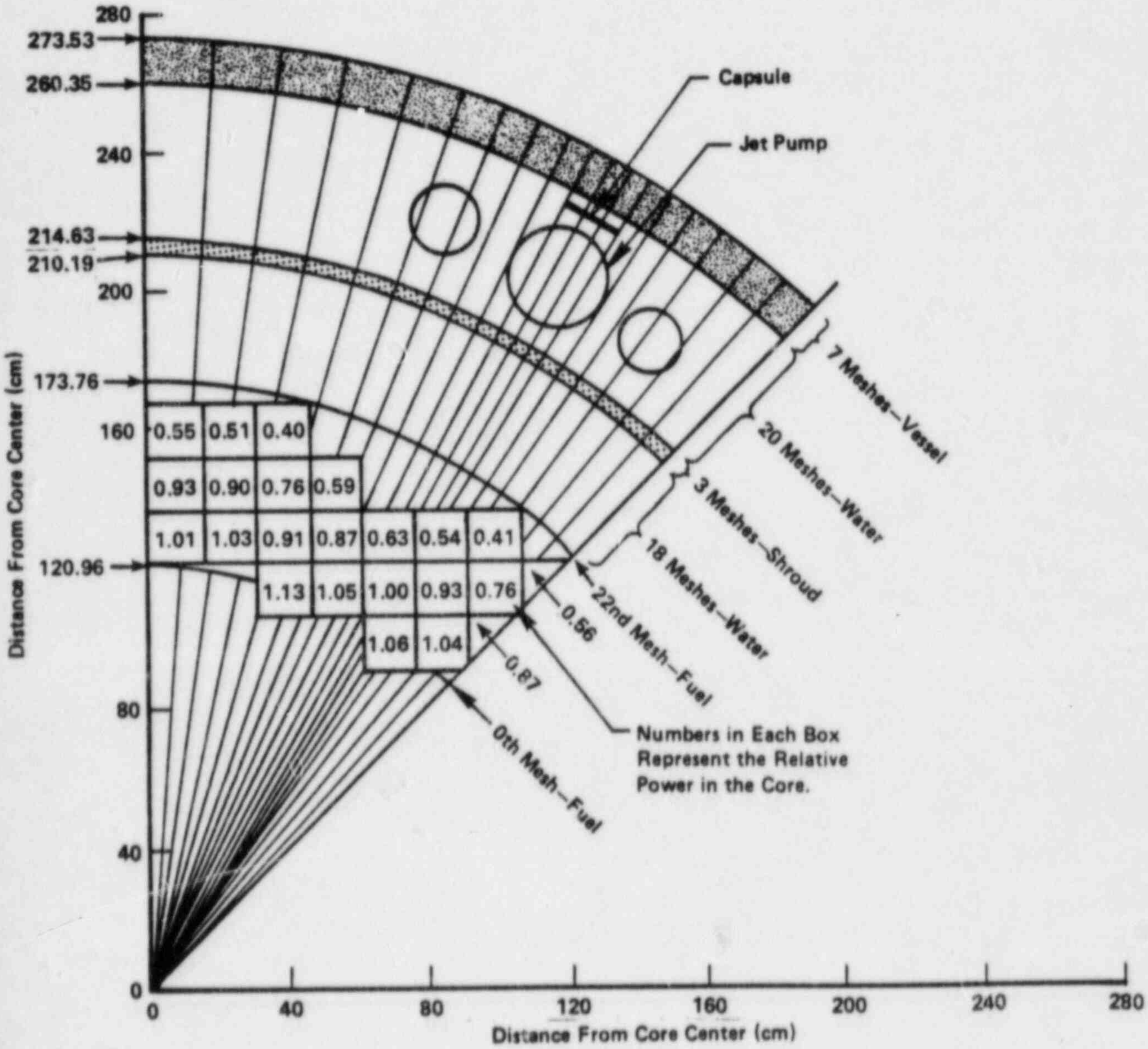


FIGURE 7. VERMONT YANKEE CORE, INTERNAL VESSEL STRUCTURES, AND VESSEL WALL GEOMETRY USED IN THE DOT CALCULATION

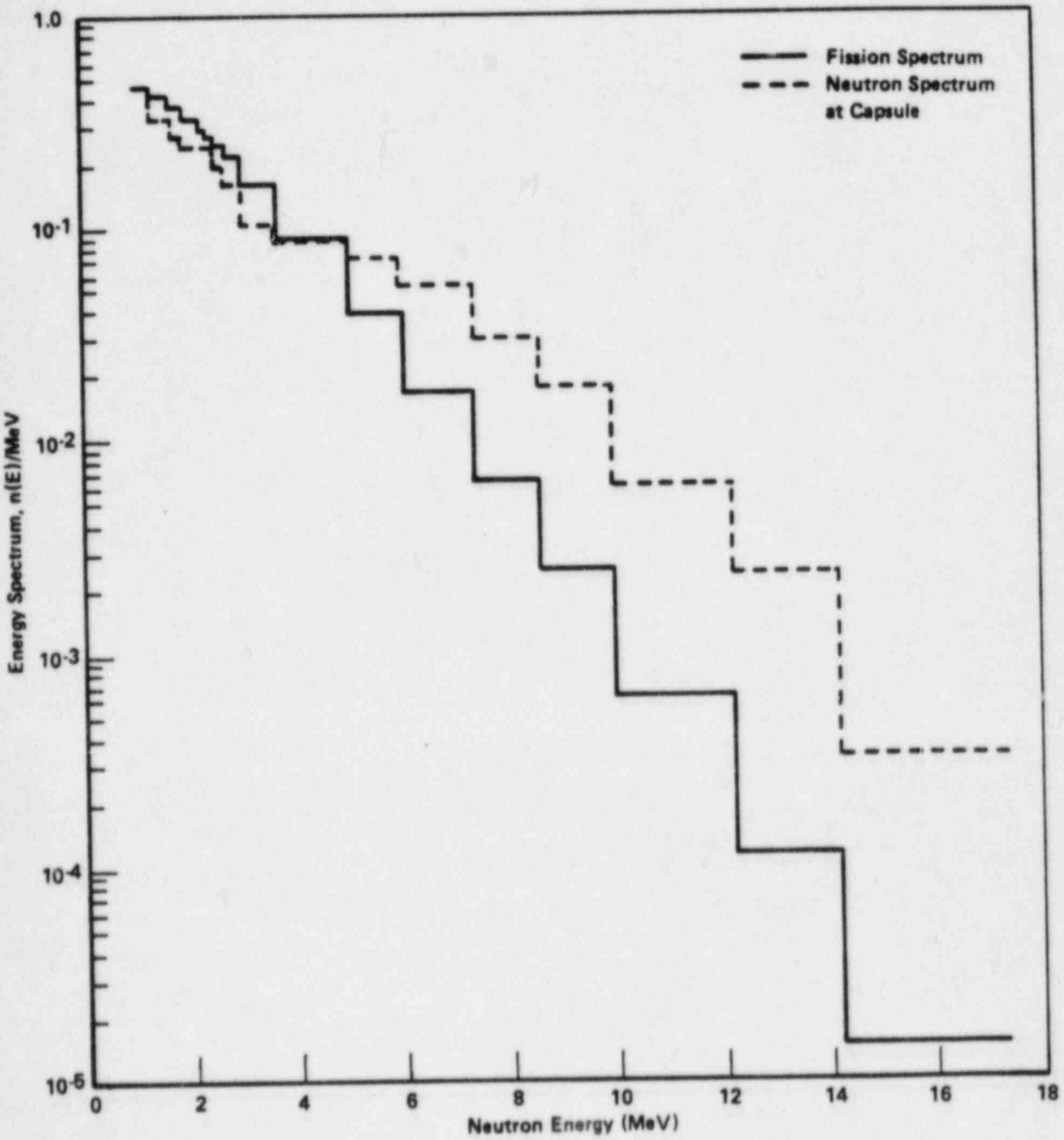


FIGURE 8. COMPARISON OF DOT SPECTRUM WITH FISSION SPECTRUM AT THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

Based upon the fluxes calculated by DOT at r meshes 60 and 61 and mesh 8 (the meshes used to represent the capsule and the region in which the flux monitors were placed), effective cross sections $_{R}$ (E 0.1 MeV) and $_{R}$ (E 1.0 MeV) defined as:

$$\sigma_R\ (E > E_C) = \frac{\int_0^{\infty} \sigma(E)\ \phi\ (E)dE}{\sigma(E_C)\ \phi\ (E)dE}$$

were calculated for iron, nickel, and copper. The results are shown in Table 3.

Other nuclear constants needed in the third step of the flux-finding procedure are given in Table 4.

In the third step, the full power flux at the capsule location is determined from the radioactivity induced in the monitor foils, the effective cross sections calculated for the monitor elements, and the power history of the reactor during capsule exposure. The fluence at the capsule is then calculated from the integrated power output of the reactor during the exposure interval using the equations outlined in the Experimental Procedures Section of this report.

$$\phi(E > E_C) = A/N\ \sigma(E > E_C)\ C$$

This equation was used to find fluxes based on the surveillance capsule activations. The time intervals were taken as one month each and a time integrated relative power value for each month and for each fuel assembly was used for the fractional power level values.

Calculations of the flux and fluence were made with the DECAY code. The reactor power history was supplied in a private communication.(26)

TABLE 3. CROSS-SECTIONS FOR THE IRRADIATED FLUX MONITORS CALCULATED FROM FLUXES AT CAPSULE CENTER OF VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

| Dosimeter Material | Cross-Sections (Barns) | |
|---|---|---|
| | E > 0.1 MeV | E > 1.0 MeV |
| Fe | $9.77 \times 10^{-2}$ | $1.72 \times 10^{-1}$ |
| Cu | $2.03 \times 10^{-3}$ | $3.58 \times 10^{-3}$ |
| Ni | $1.24 \times 10^{-1}$ | $2.18 \times 10^{-1}$ |

TABLE 4. CONSTANTS USED IN DOSIMETRY CALCULATIONS FOR THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

| Reaction | Target, percent | Isotopic Abundance, percent | Threshold Energy, MeV | Product Half-Life |
|---|---|---|---|---|
| $^{54}Fe(n,p)^{54}Mn$ | 99.865 Fe | 5.82 | 2.5 | 312.6 days |
| $^{63}Cu(n,\alpha)^{60}Co$ | 99.999 Cu | 69.17 | 6.1 | 5.27 years |
| $^{58}Ni\ (n,p)^{58}Co$ | 99.927 Ni | 67.77 | 2.1 | 71.2 days |

## Dosimetry Results

The surveillance capsule was located at the 30-degree azimuthal position at approximately the core midplane position and about one inch from the inner pressure vessel wall. This capsule was in the reactor for 2755 equivalent full power days or about 7.54 equivalent full power years. The Vermont Yankee Nuclear Generating Plant design thermal output is 1593 $MW_t$.

The neutron monitor wires from Charpy packets G1, G2 and G3 were counted to determine their specific activity. The recommended ASTM procedures(27-31) were followed in determining the specific activity of the wires. Each dosimeter monitor consisted of an approximately 4-inch length of wire which was rolled into a small coil for counting. The count rate was determined for each wire. The fast flux and fluence calculated using the count rate therefore represented an average over the 4-inch length of that wire. The >0.1 MeV and >1.0 MeV full power flux and fluence calculated from initial startup to March 1983 are given in Table 5 and Table 6, respectively, for each of the dosimeter wires along with the average of the flux and fluence derived from each wire and the average values for Fe, Cu, and Ni. In addition, the average values of the three results are given.

Using the average fluxes of $3.18 \times 10^8$ n/cm$^2$/sec for E > 0.1 MeV and $1.80 \times 10^8$ n/cm$^2$/sec for E > 1.0 MeV, the fluxes at full power at the inside of the pressure vessel wall, at 1/4 T and at 3/4 T directly behind the capsule (30-degree orientation) and at the maximum position ( 0-degree orientation) were calculated. The flux results are tabulated in Table 6. The end of life (EOL) fluences were also calculated and tabulated in Table 6 assuming a reactor pressure vessel lifetime of 40 years and the reactor operated at 80 percent of full power. The fine mesh and time integrated relative power values shown in Figure 7 for each fuel assembly was used in the DOT 4.3 code to generate the values in Table 7. A plot of neutron flux (E > 1.0 MeV) as a function of azimuthal angle (in degrees) is shown in Figure 9. The fluence values at the maximum position for inner vessel wall, 1/4 T and 3/4 T are plotted as a function of time in equivalent full power years (EFPY) for the Vermont Yankee pressure vessel in Figure 10. The lead factor, i.e., the ratio of the flux (E > 1.0 MeV) at the surveillance capsule to the largest flux

TABLE 5. FLUX AND FLUENCE VALUES AT THE WITH ENERGY GREATER THAN 0.1 MEV AT THE VERMONT YANKEE SURVEILLANCE CAPSULE (30-DEGREE AZIMUTHAL POSITION)

| Dosimeter Material | Full Power Flux (n/cm$^2$/sec) x $10^9$ | Fluence* (n/cm$^2$) x $10^{17}$ |
|---|---|---|
| Fe (G1) | 3.086 | 7.346 |
| (G2) | 3.204 | 7.627 |
| (G3) | 3.086 | 7.346 |
| Average of Fe | 3.125 | 7.440 |
| Cu (G1) | 3.238 | 7.709 |
| (G2) | 3.444 | 8.197 |
| (G3) | 3.216 | 7.655 |
| Average of Cu | 3.299 | 7.854 |
| Ni (G1) | 3.107 | 7.396 |
| (G2) | 3.207 | 7.633 |
| (G3) | 3.001 | 7.144 |
| Average of Ni | 3.105 | 7.391 |
| Average of Fe Cu, and Ni | 3.176 | 7.562 |

*Fluence based on 2755 equivalent full power days.

TABLE 6. FLUX AND FLUENCE VALUES AT THE WITH ENERGY GREATER THAN 1.0 MEV AT THE VERMONT YANKEE SURVEILLANCE CAPSULE (30-DEGREE AZIMUTHAL POSITION)

| Dosimeter Material | Full Power Flux (n/cm$^2$/sec) x $10^8$ | Fluence* (n/cm$^2$) x $10^{16}$ |
|---|---|---|
| Fe (G1) | 1.753 | 4.173 |
| (G2) | 1.820 | 4.332 |
| (G3) | 1.753 | 4.173 |
| Average of Fe | 1.775 | 4.226 |
| Cu (G1) | 1.839 | 4.377 |
| (G2) | 1.955 | 4.655 |
| (G3) | 1.826 | 4.347 |
| Average of Cu | 1.873 | 4.460 |
| Ni (G1) | 1.765 | 4.201 |
| (G2) | 1.821 | 4.336 |
| (G3) | 1.705 | 4.058 |
| Average of Ni | 1.764 | 4.198 |
| Average of Fe, Cu, and Ni | 1.804 | 4.295 |

*Fluence based on 2755 equivalent full power days.

## TABLE 7. FLUX AND FLUENCE IN THE PRESSURE VESSEL WALL OF THE VERMONT YANKEE REACTOR - BEHIND THE SURVEILLANCE CAPSULE (30-DEGREE) AND AT THE AZIMUTHAL ANGLE OF MAXIMUM FLUX IN VESSEL WALL (0-DEGREE)

| | | Full Power Flux in Vessel | | Fluence in Vessel | | | |
|---|---|---|---|---|---|---|---|
| | | | | Behind Capsule (30°) | | Maximum (0°) | |
| Energy (MeV) | Location | Behind Capsule (30°) ($n/cm^2/sec \times 10^8$) | Maximum (0°) ($n/cm^2/sec \times 10^8$) | Mar. 83 (1) ($\times 10^{16}$ $n/cm^2$) | EOL (2) ($\times 10^{17}$ $n/cm^2$) | Mar. 83 (1) ($\times 10^{16}$ $n/cm^2$) | EOL (2) ($\times 10^{17}$ $n/cm^2$) |
| 0.1 | Surface | 2.04 | 3.85 | 4.85 | 2.06 | 9.16 | 3.89 |
| 0.1 | 1/4 T | 1.83 | 3.52 | 4.35 | 1.85 | 8.38 | 3.55 |
| 0.1 | 3/4 T | 0.953 | 1.82 | 2.26 | 0.962 | 4.33 | 1.84 |
| 1.0 | Surface | 0.977 | 2.18 | 2.32 | 0.987 | 5.19 | 2.20 |
| 1.0 | 1/4 T | 0.712 | 1.59 | 1.69 | 0.719 | 3.78 | 1.61 |
| 1.0 | 3/4 T | 0.285 | 0.623 | 0.678 | 0.288 | 1.48 | 0.629 |

(1) Fluence based on 7.54 effective full power years.

(2) Fluence based on 32 effective full power years.

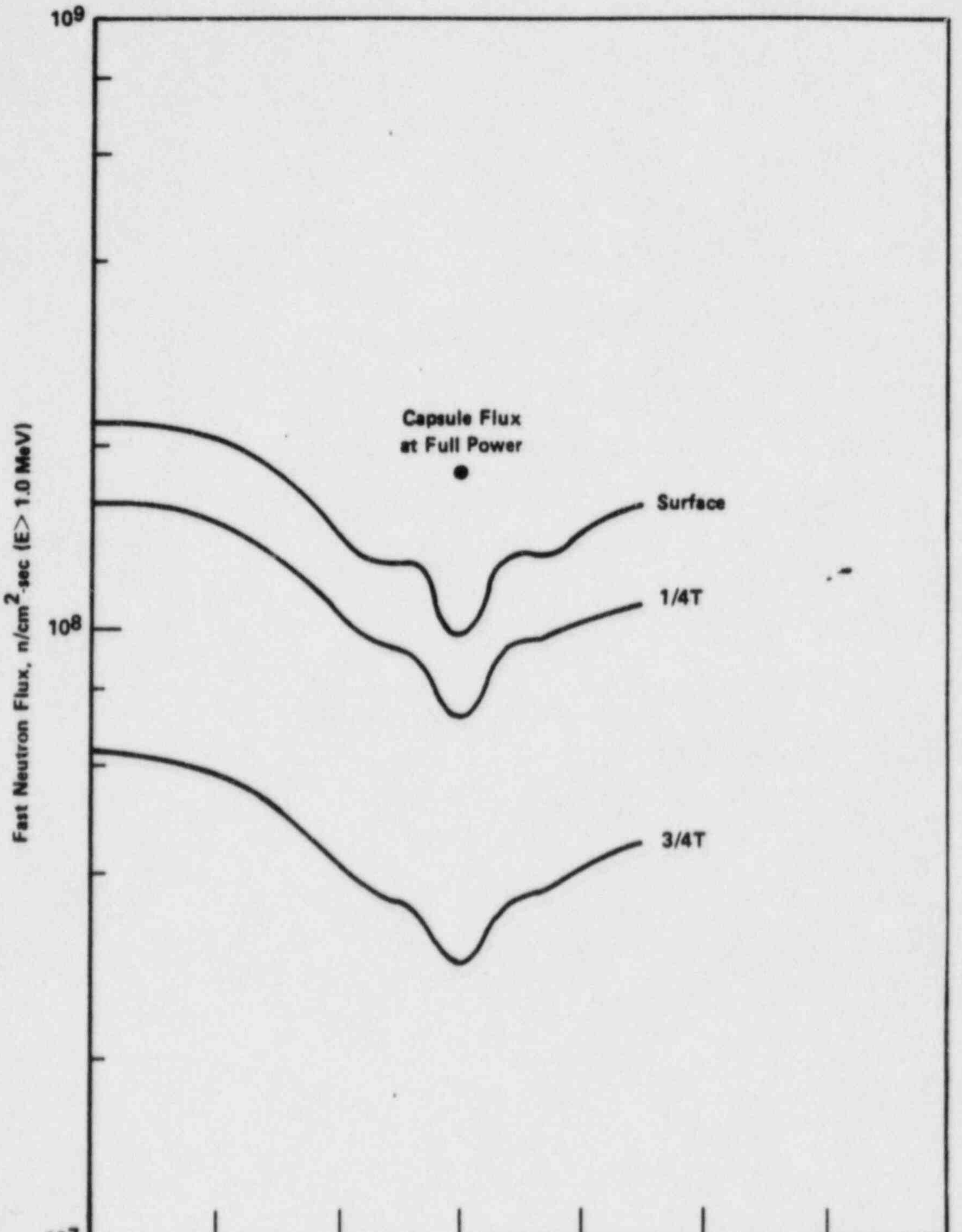


FIGURE 9. CALCULATED FLUX (E > 1 MeV) AT THE VERMONT YANKEE 30-DEGREE CAPSULE, INNER WALL, 1/4 THICKNESS, AND 3/4 THICKNESS AS A FUNCTION OF AZIMUTHAL ANGLE

($E > 1.0$ MeV) received by the vessel wall at any azimuthal location, is approximately 0.83 ($1.80 \times 10^8/2.18 \times 10^8$) at the vessel surface. This result indicates that the flux at the capsule actually lags the flux at certain vessel wall positions. The lead factors at the pressure vessel 1/4 T and 3/4 T positions were calculated to be 1.13 ($1.80 \times 10^8/1.59 \times 10^8$) and 2.89 ($1.80 \times 10^8/6.23 \times 10^7$), respectively.

The peak neutron fluence ($E > 1$ MeV) at the end of life (EOL) for the pressure vessel surface was predicted to be between 2.0 and $2.9 \times 10^{17}$ $n/cm^2$ in the final report of May 23, 1975 by Southwest Research Institute on "Vessel Material Surveillance Program for Vermont Yankee Nuclear Power Station". The BCL calculated surface EOL fast fluence value of $2.2 \times 10^{17}$ $n/cm^2$ agrees well with these previously reported values. The accuracy of the fluence values generated at BCL is estimated to be ± 20 percent. Although specific activities of fluence monitor wires can be determined to ± 5 percent accuracies, uncertainties in neutron spectrum and spectrum averaged cross sections result in the larger variances in the computed flux and fluence values.

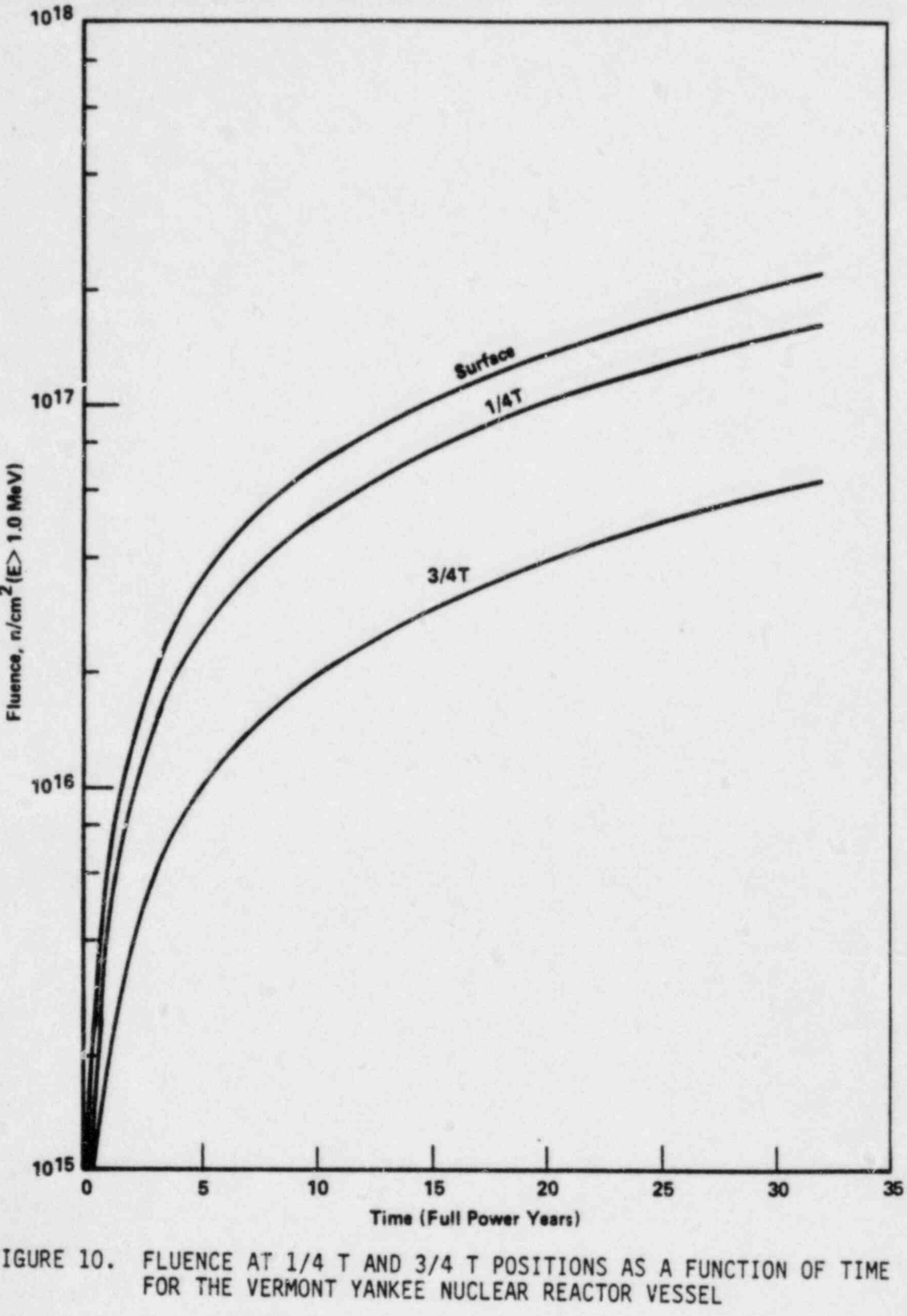


FIGURE 10. FLUENCE AT 1/4 T AND 3/4 T POSITIONS AS A FUNCTION OF TIME FOR THE VERMONT YANKEE NUCLEAR REACTOR VESSEL

## 6.2 Charpy Impact Properties

### Introduction

A reactor pressure vessel receives a significant fast neutron exposure during operation and is therefore subject to radiation-induced embrittlement. Charpy V-notch specimens were fabricated and irradiated in a Vermont Yankee surveillance capsule at the 30 degree azimuthal position and about one inch from the vessel wall. The specimens were then removed and tested.

Appendix G of the ASME Boiler and Pressure Vessel Code, Section III, Division 1 (Nuclear Power Plant Components) presents a procedure for obtaining allowable loading for ferritic pressure retaining materials to protect against nonductile failure. The procedure is based on the principles of linear elastic fracture mechanics.

### Analytical Method

Charpy V-notch tests were conducted over a range of temperatures. The impact energy, lateral expansion, and fracture appearance for the irradiated specimens were determined from the tests which followed ASTM procedures.(22) Plots of impact property versus test temperature were plotted for each type of specimen (base metal, weld metal, and HAZ metal) using the hyperbolic tangent fit. From these data, the temperatures at which 30 ft-lb, 50 ft-lb, and 35 mil lateral expansion occurred were determined and the upper shelf energy for each type of specimen was also determined.

## Charpy Impact Test Results

Twelve irradiated base metal Charpy V-notch impact specimens, twelve irradiated weld metal Charpy V-notch impact specimens, and twelve irradiated HAZ metal Charpy V-notch specimens were tested. The results of tests conducted between 0 and 320 F for the base metal specimens are listed in Table 8. The results of tests conducted between -80 and 320 F for the weld metal specimens are listed in Table 9 and the results of tests conducted between -80 and 320 F for the HAZ metal specimens are listed in Table 10. In addition to the total impact energy values, the measured lateral expansion values and the estimated fracture appearance for each specimen are also listed in Tables 8, 9 and 10. The total impact energy is the amount of energy absorbed by the specimen tested at the indicated temperature. Lateral expansion is a measure of the plastic "shear lip" deformation produced by the striking edge of the impact machine hammer when it impacts the specimen. Lateral expansion is determined by the change of specimen thickness directly adjacent to the notch location. Fracture appearance is a visual estimate of the amount of shear (ductile type of fracture) appearing on the specimen fracture surface. Additional data, along with a discussion of test results and of the procedures for conducting instrumented Charpy V-notch impact testing, is given in Appendix A.

Plots of the impact properties (impact energy, lateral expansion, and fracture appearance) versus test temperature are graphically illustrated in Figures 11 through 19. These figures show the change in impact properties as a function of temperature. Figures 20, 21, and 22 show the fracture surfaces of the Charpy specimens. A summary of the Vermont Yankee surveillance capsule Charpy V-notch impact test data (including the 30 and 50 ft-lb transition temperatures, the 35 mil lateral expansion temperature, and the upper shelf energy) is given in Table 11.*

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*Text continued on page 58.

TABLE 8. CHARPY V-NOTCH IMPACT RESULTS FOR IRRADIATED BASE METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

| Specimen Identification | Test Temperature, F | Impact Energy, ft-lb | Lateral Expansion, mils | Fracture Appearance, Percent Shear |
|---|---|---|---|---|
| JB1 | 0 | 12.5 | 14.0 | 10 |
| JBK | 10 | 28.0 | 26.2 | 20 |
| JBT | 20 | 17.5 | 19.6 | 15 |
| JB3 | 20 | 32.0 | 28.8 | 20 |
| JCC | 40 | 35.0 | 33.6 | 20 |
| JD1 | 50 | 50.5 | 41.4 | 25 |
| JBB | 60 | 54.0 | 45.8 | 35 |
| JBJ | 80 | 76.0 | 59.8 | 55 |
| JBD | 120 | 92.0 | 71.2 | 70 |
| JCA | 160 | 124.0 | 88.8 | 100 |
| JDJ | 240 | 127.0 | 90.0 | 100 |
| JC5 | 320 | 128.0 | 88.8 | 100 |

Instrumented results are contained in Appendix A, Table A-1.

TABLE 9. CHARPY V-NOTCH IMPACT RESULTS FOR IRRADIATED WELD METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

| Specimen Identification | Test Temperature, F | Impact Energy, ft-lb | Lateral Expansion, mils | Fracture Appearance, Percent Shear |
|---|---|---|---|---|
| JE5 | -80 | 28.0 | 22.8 | 25 |
| JKP | -40 | 29.0 | 27.0 | 30 |
| JEU | -30 | 44.0 | 40.2 | 40 |
| JJL | -20 | 49.0 | 43.2 | 40 |
| JKM | 0 | 30.0 | 28.8 | 30 |
| JJT | 0 | 55.5 | 51.2 | 45 |
| JJ7 | 19 | 67.0 | 54.8 | 60 |
| JJB | 40 | 68.5 | 58.8 | 60 |
| JKE | 80 | 99.0 | 77.0 | 80 |
| JEC | 160 | 120.5 | 91.8 | 100 |
| JJ3 | 240 | 121.0 | 93.8 | 100 |
| JJM | 320 | 114.5 | 89.8 | 100 |

(a) Instrumented results are contained in Appendix A, Table A-2.

TABLE 10. CHARPY V-NOTCH IMPACT RESULTS FOR IRRADIATED HAZ METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

| Specimen Identification | Test Temperature, F | Impact Energy, ft-lb | Lateral Expansion, mils | Fracture Appearance, Percent Shear |
|---|---|---|---|---|
| JPA | -80 | 11.5 | 9.8 | 10 |
| JP3 | -40 | 23.0 | 19.4 | 15 |
| JLT | -20 | 12.5 | 13.6 | 15 |
| JL7 | -20 | 63.5 | 50.8 | 60 |
| JP6 | 0 | 15.0 | 15.6 | 20 |
| JP2 | 0 | 45.5 | 40.8 | 50 |
| JLD | 20 | 40.5 | 39.6 | 45 |
| JPB | 40 | 70.5 | 56.2 | 70 |
| JP4 | 80 | 56.5 | 48.2 | 60 |
| JM6 | 160 | 105.5 | 78.4 | 100 |
| JPC | 240 | 116.0 | 87.0 | 100 |
| JMD | 320 | 112.5 | 87.6 | 100 |

(a) Instrumented results are contained in Appendix Table A, Table A-3.

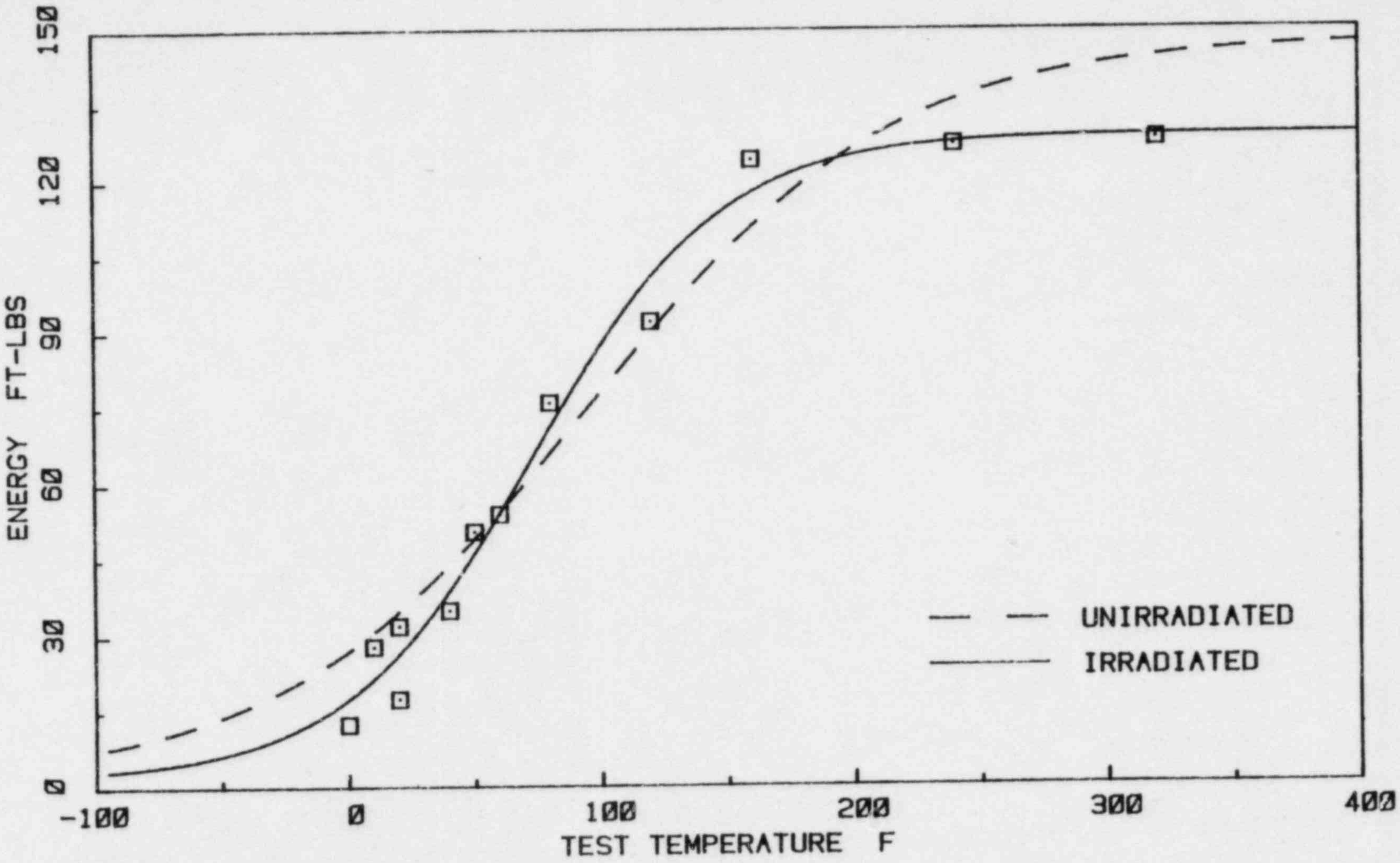

FIGURE 11. CHARPY V-NOTCH IMPACT ENERGY VERSUS TEST TEMPERATURE FOR THE IRRADIATED BASE METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

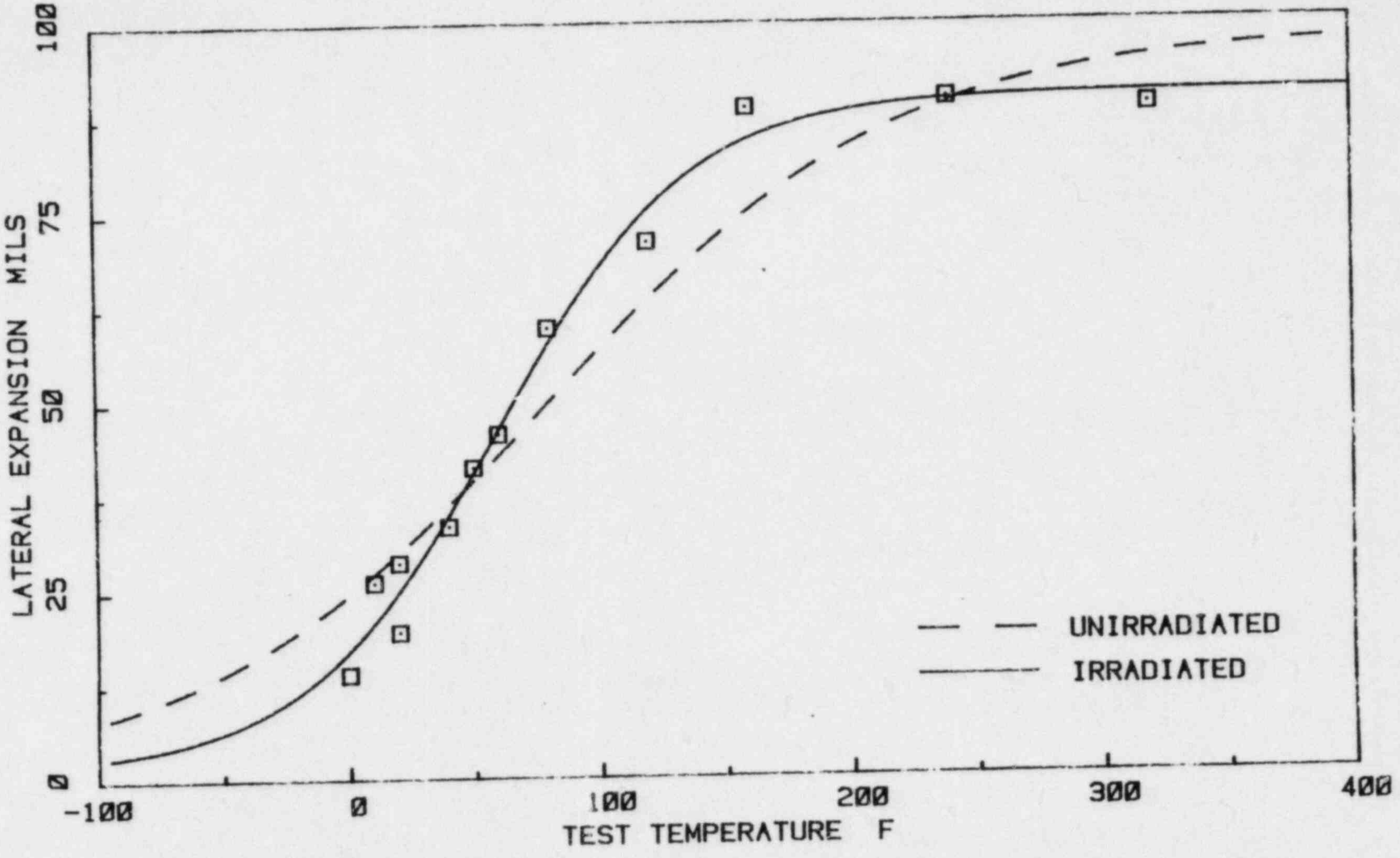

FIGURE 12. CHARPY V-NOTCH LATERAL EXPANSION VERSUS TEST TEMPERATURE FOR THE IRRADIATED BASE METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

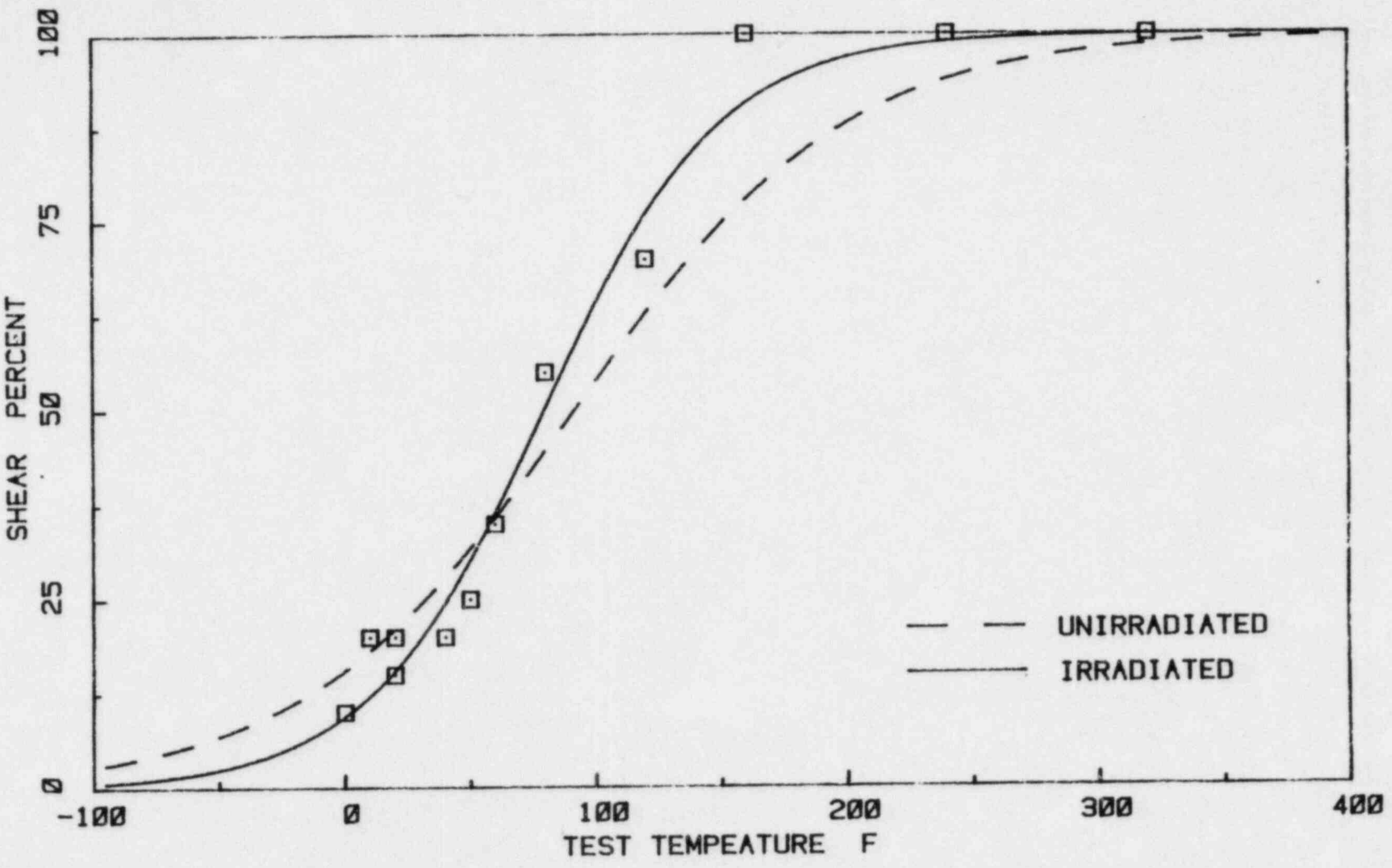

FIGURE 13. CHARPY V-NOTCH PERCENT DUCTILE SHEAR VERSUS TEST TEMPERATURE FOR THE IRRADIATED BASE METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

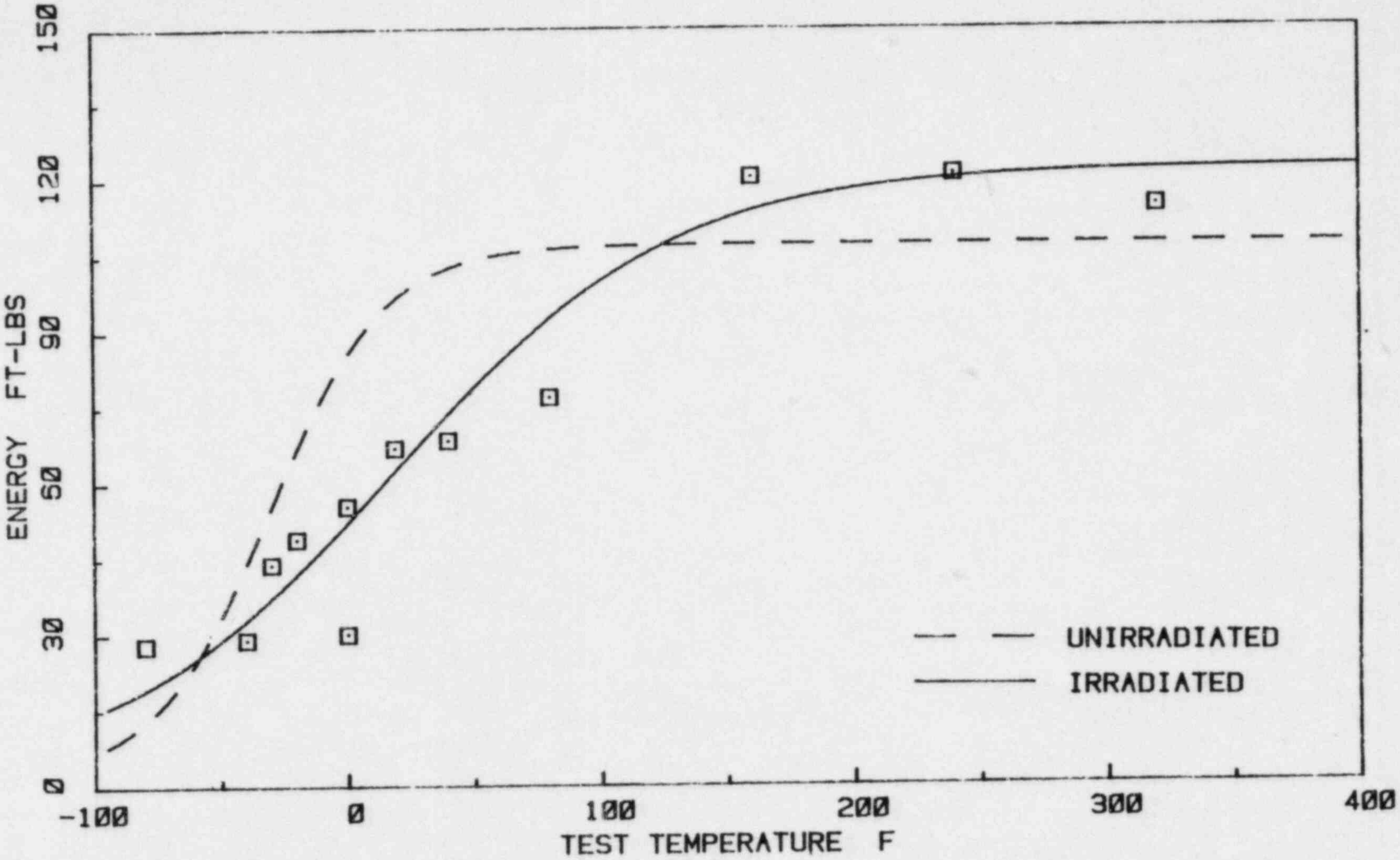

FIGURE 14. CHARPY V-NOTCH IMPACT ENERGY VERSUS TEST TEMPERATURE FOR THE IRRADIATED WELD METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

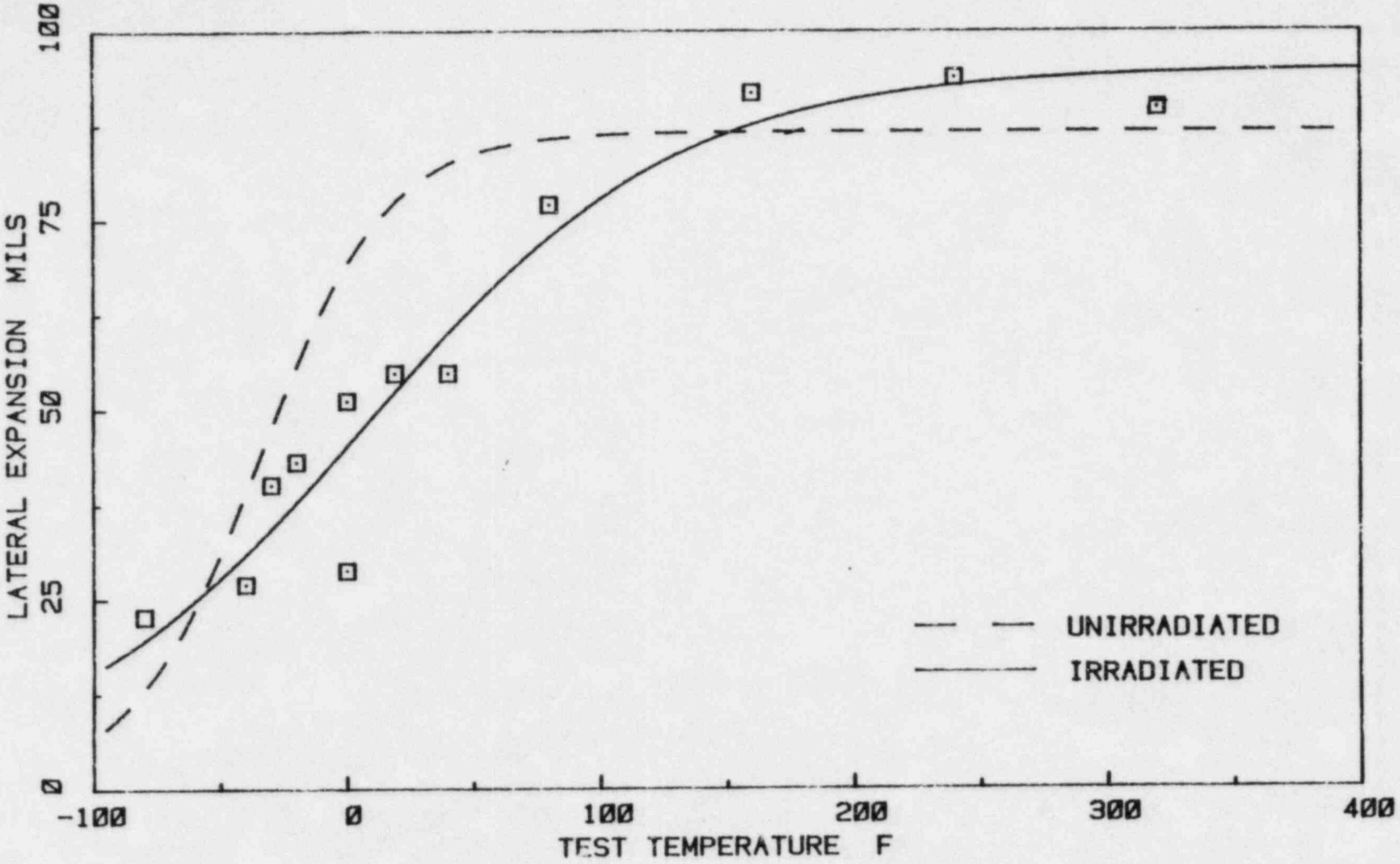

FIGURE 15. CHARPY V-NOTCH LATERAL EXPANSION VERSUS TEST TEMPERATURE FOR THE IRRADIATED WELD METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

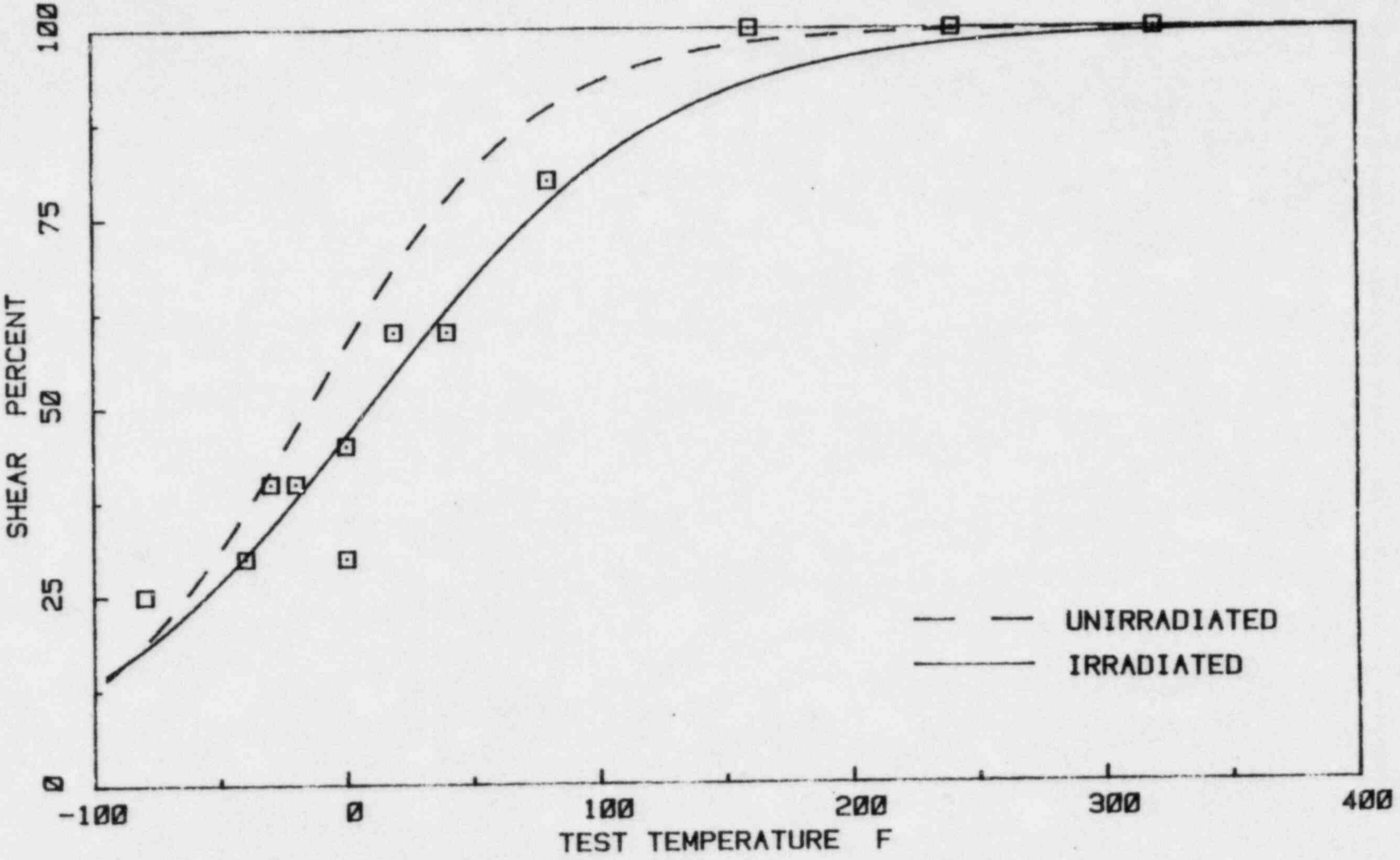

FIGURE 16. CHARPY V-NOTCH PERCENT DUCTILE SHEAR VERSUS TEST TEMPERATURE FOR THE IRRADIATED WELD METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

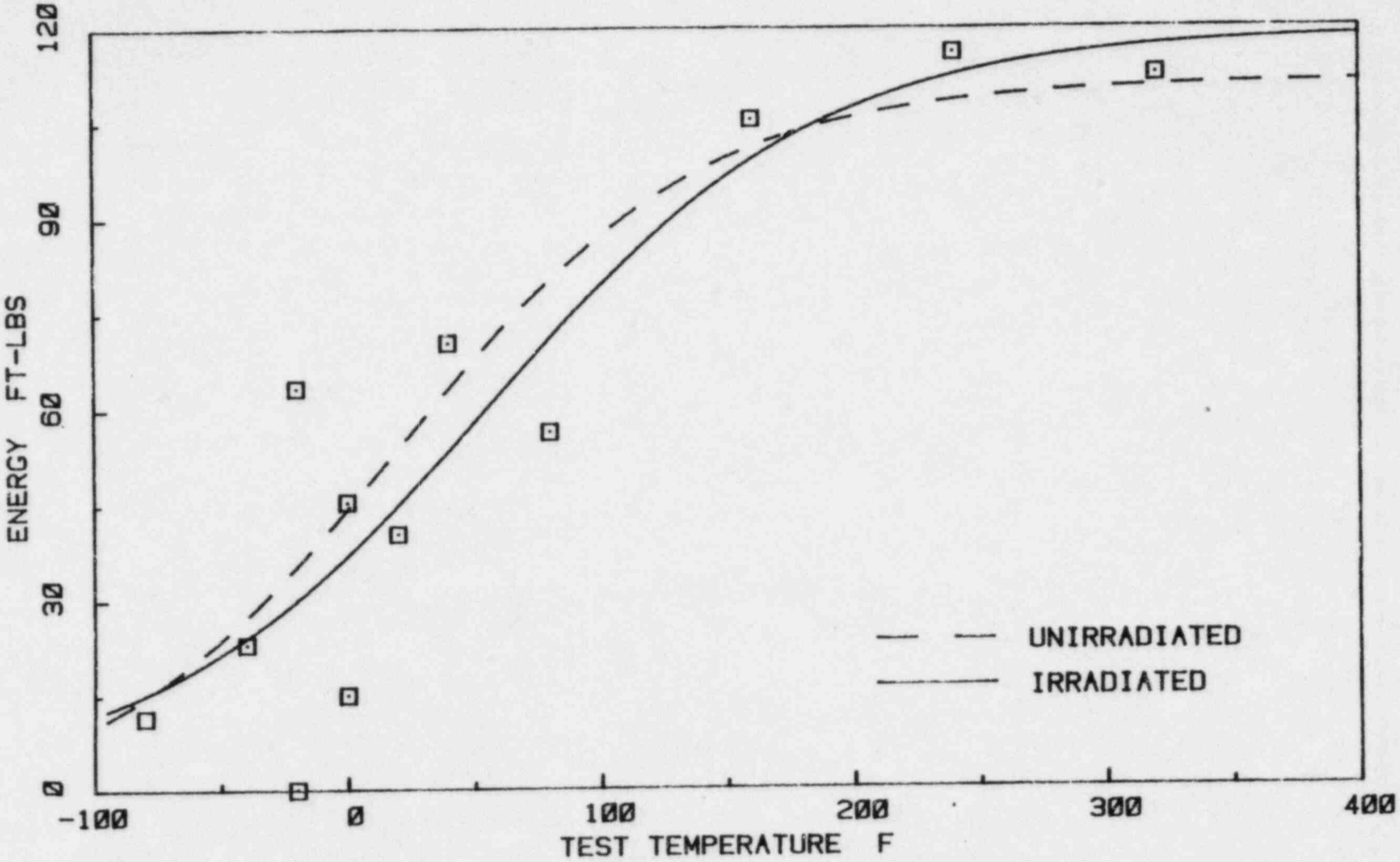

FIGURE 17. CHARPY V-NOTCH IMPACT ENERGY VERSUS TEST TEMPERATURE FOR THE IRRADIATED HAZ METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

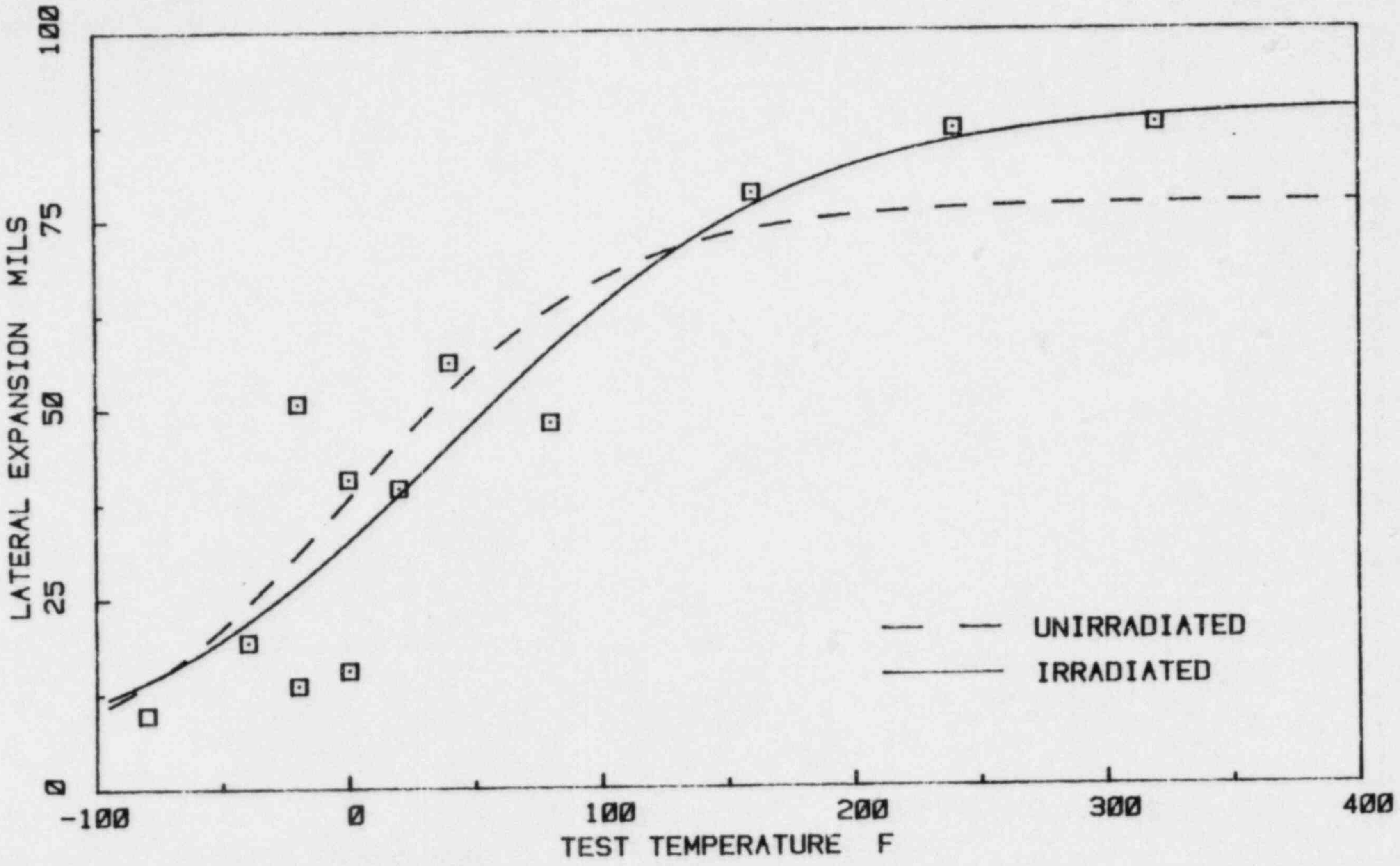

FIGURE 18. CHARPY V-NOTCH LATERAL EXPANSION VERSUS TEST TEMPERATURE FOR THE IRRADIATED HAZ METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

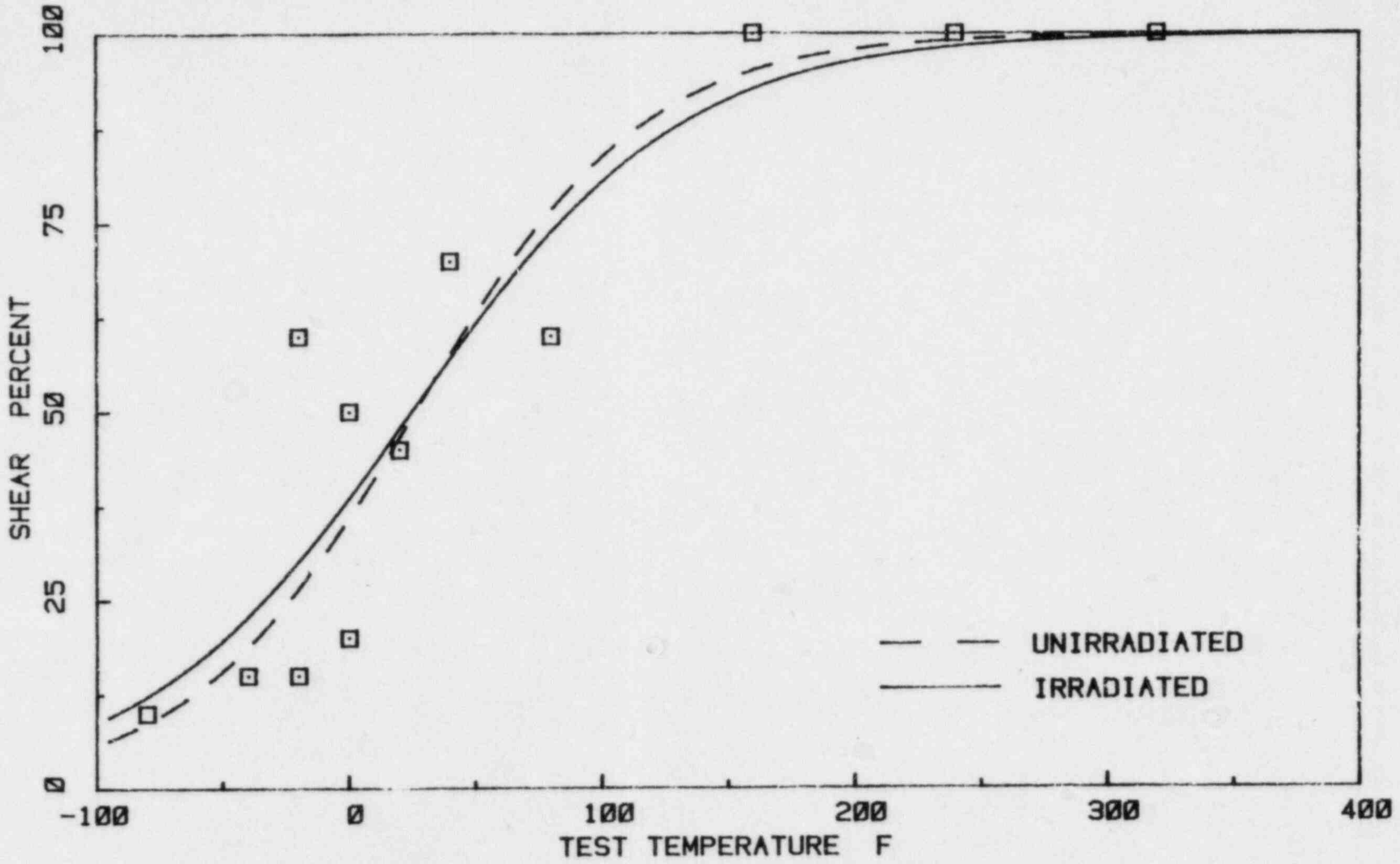

FIGURE 19. CHARPY V-NOTCH PERCENT DUCTILE SHEAR VERSUS TEST TEMPERATURE FOR THE IRRADIATED HAZ METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

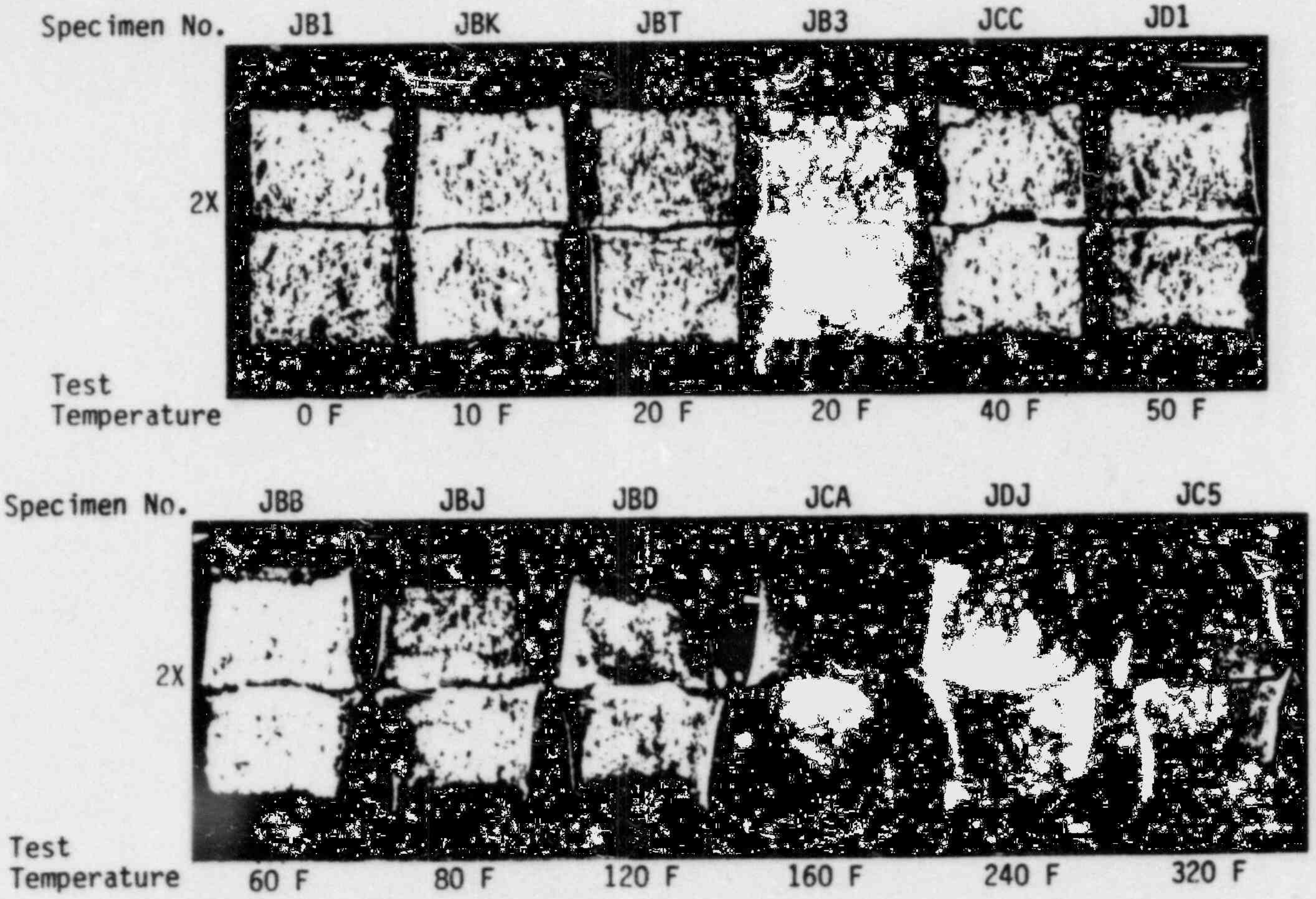

FIGURE 20. CHARPY IMPACT SPECIMEN FRACTURE SURFACES FOR THE IRRADIATED BASE METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

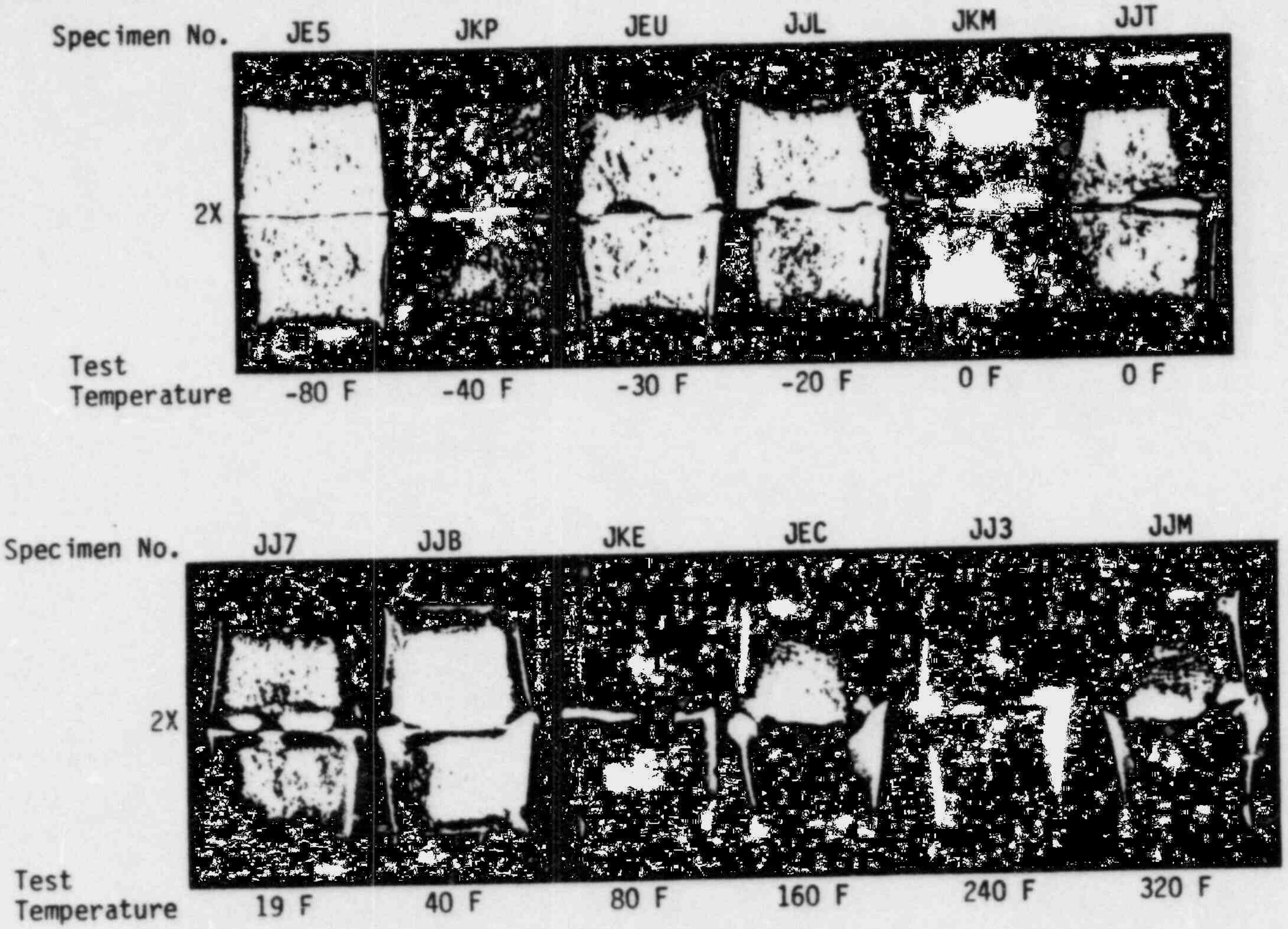

FIGURE 21. CHARPY IMPACT SPECIMEN FRACTURE SURFACES FOR THE IRRADIATED WELD METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

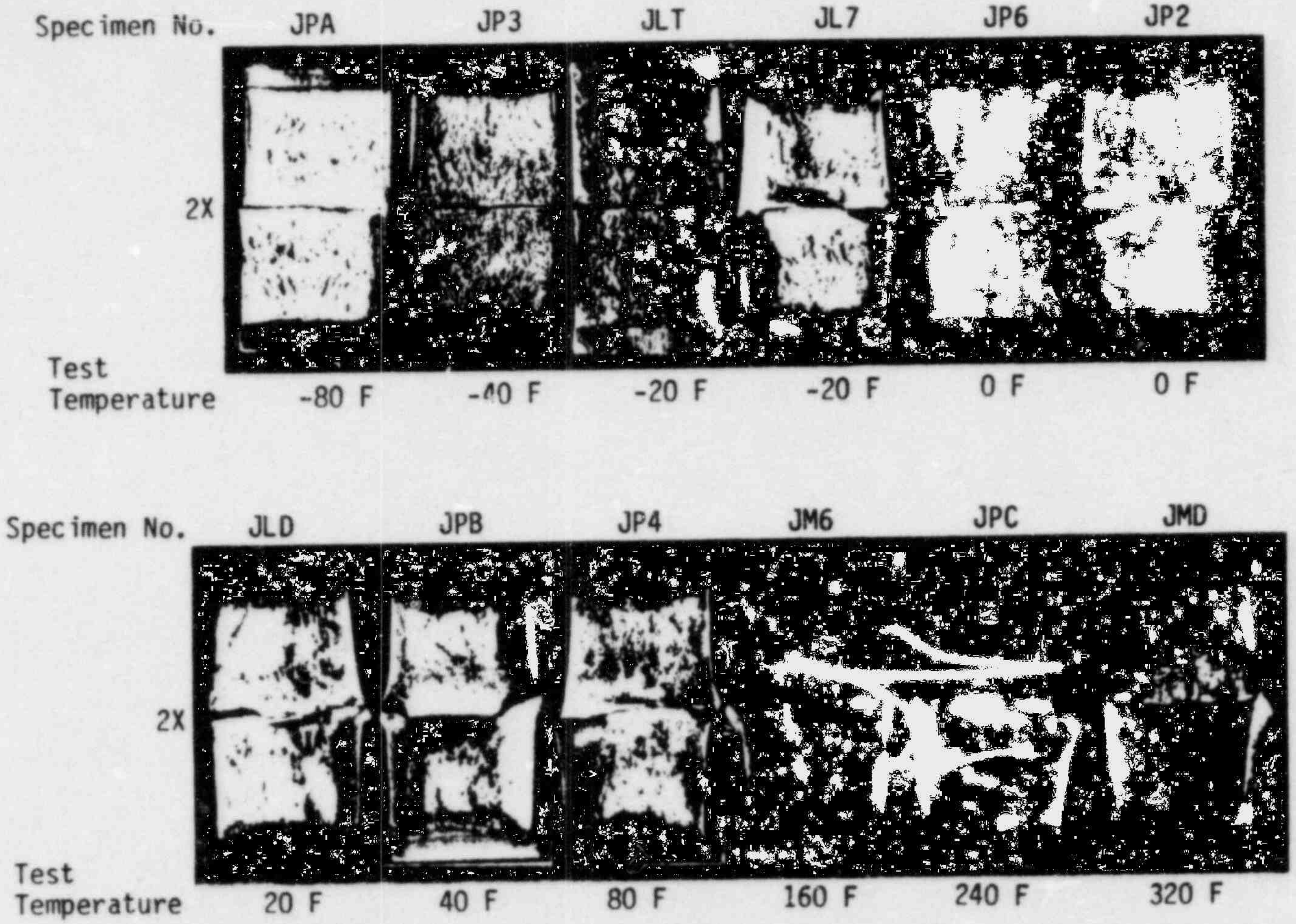

FIGURE 22. CHARPY IMPACT SPECIMEN FRACTURE SURFACES FOR THE IRRADIATED HAZ METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

## TABLE 11. SUMMARY OF CHARPY IMPACT PROPERTIES FOR IRRADIATED MATERIALS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

| Material | E > 1.0 MeV Fluence, n/cm$^2$ | 30 ft-lb Transition Temperature, F | 50 ft-lb Transition Temperature, F | 35-Mil Lateral Expansion Temperature, F | Upper Shelf Energy, ft-lb |
|---|---|---|---|---|---|
| Base | 0 | 8 | 52 | 35 | 148 |
| Weld | 0 | -50 | -35 | -45 | 107 |
| HAZ | 0 | -30 | 13 | -10 | 110 |
| Base | $4.30 \times 10^{16}$ | 27 | 60 | 40 | 128 |
| Weld | $4.30 \times 10^{16}$ | -45 | -5 | -28 | 122 |
| HAZ | $4.30 \times 10^{16}$ | -15 | 35 | 5 | 117 |
| Base | change | 19 | 8 | 5 | -20 |
| Weld | change | 5 | 30 | 17 | 15 |
| HAZ | change | 15 | 22 | 15 | 7 |

Unirradiated archive baseline Charpy V-notch impact data were obtained by Battelle for material from the base, weld, and HAZ metal locations.(33) The 30 ft-lb, 50 ft-lb, and 35-mil lateral expansion index temperatures were obtained, as well as the upper shelf energy. These data are also given in Table 11. By difference, the shift in transition temperatures can be calculated for each index. The shift or changes in 30 and 50 ft-lb transition temperatures, 35-mil lateral expansion temperature, and upper shelf energy are also given in Table 11. The shifts range from 5 to 30 F. The upper shelf energy for the base metal has dropped 20 ft-lb to 128 ft-lb. However, the predicted EOL upper shelf energy, as estimated from Regulatory Guide 1.99, is not expected to drop below 90 ft-lb. This is well above the minimum allowable EOL value of 50 ft-lb specified in 10 CFR 50 Appendix G.

The initial reference nil-ductility transition temperature ($RT_{NDT}$) was established previously for the Vermont Yankee unirradiated base and weld metals as 60 F(17). The most recent Nuclear Regulatory Commission (NRC) ruling (May 27, 1983) for Appendix G to 10 CFR 50, "Fracture Toughness Requirements for Light-Water Nuclear Power Reactors", specifies that an adjusted $RT_{NDT}$ for irradiated specimens can be determined by adding to the initial $RT_{NDT}$ the amount of temperature shift measured at the 30 ft-lb level in the average Charpy curve for the irradiated material relative to that of the unirradiated material. The material with the largest measured reference temperature shift is then the limiting material. The Vermont Yankee pressure vessel base metal exhibited the largest 30 ft-lb shift (19 F) and therefore is the limiting material for this reactor. The adjusted $RT_{NDT}$ was calculated by adding the initial reference temperature to the 30 ft-lb shift and was found to be 79 F (60 F + 19 F) for the 30-degree surveillance capsule specimens. Because the surveillance capsule lead factor is greater than one (1.13) for the maximum fluence location (0-degree) and at the pressure vessel 1/4 T position, the value of 79 F for the adjusted $RT_{NDT}$ is conservative. This adjusted reference temperature can be used in revising the plant pressure-temperature operating curves. Using Regulatory Guide 1.99, the predicted end of life (EOL) shift in $RT_{NDT}$ (assuming 32 EFPY) was estimated to be at most about 40 F for the pressure vessel maximum fluence position and at the 1/4 T wall position. This compares exactly with the predicted lifetime shift of

40 F found in the Southwest Research Institute Final Report of May 23, 1975, "Vessel Material Surveillance Program for Vermont Yankee Nuclear Power Station".

## 6.3 Tensile Properties

### Introduction

The tensile specimens were irradiated in the Vermont Yankee surveillance capsule which was located at the 30 degree azimuthal position and about 0.56 inch from the vessel wall. The tensile specimens were tested and the yield strength, ultimate tensile strength, uniform elongation, total elongation, and reduction-in-area of the irradiated materials were determined.

### Analytical Method

Prior to testing, each tensile specimen diameter was measured using a blade micrometer and an initial cross-sectional area was calculated for each specimen. Load-elongation data were recorded on a strip chart for each test. The 0.2 percent offset yield load, maximum tensile load, uniform elongation, and total elongation data were taken directly from the strip chart. The percent elongation was calculated for a one inch gage section and was verified by posttest measurements of the increase in distance between the tensile specimen punch marks (originally positioned one inch apart). The yield load and ultimate load divided by the initial cross-sectional area provided the yield and ultimate tensile strengths, respectively. The percent reduction-in-area was calculated by subtracting the posttest cross-sectional area from the initial cross-sectional area, dividing by the initial cross-sectional area, and multiplying by 100. The fracture strength was calculated by dividing the failure load by the pretest cross-sectional area and the fracture stress was calculated by dividing the failure load by the posttest cross-sectional area.

## Tensile Test Results

The tensile test parameters and irradiated specimen tensile properties are listed in Table 12 and plotted in Figures 23 and 24. This table lists the specimen number, material, and test temperature. Also listed are the 0.2 percent offset yield strength, ultimate tensile strength, fracture strength, fracture stress, reduction in area, uniform elongation, and total elongation for each specimen tested. Photographs of the tested tensile specimen (longitudinal and end-on) are shown in Figures 25, 26 and 27. As can be seen, the necking occurred between the initial 1 inch punch marks for all nine tensile specimens and all failures were in a ductile cup-and-cone mode.

Tensile tests were conducted at room temperature (75 F), 180 F, and 543 F. All three materials, base metal, weld metal, and HAZ metal exhibited decreases in yield strength, ultimate strength, and fracture strength when the test temperature was increased from room temperature to 180 F. These tensile properties appear, however, to recover partially (and in some cases totally) at the test temperature of 543 F when compared with the room temperature test results. The 0.2 percent offset yield strength and fracture stress exhibited a monotonic decrease with increasing test temperature between room temperature and 543 F for all three material types. The percent reduction in area for the three materials was relatively constant at test temperatures of 75 F (room temperature) and 180 F but decreased slightly (6 to 13 percent) at a test temperature of 543 F. Within experimental standard deviation, the uniform elongation and total elongation appear to decrease when the test temperature was increased from 75 to 180 F and appears to recover at the test temperature of 543 F.*

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*Text continued on page 67.

## TABLE 12. TENSILE PROPERTIES FOR THE IRRADIATED MATERIALS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

| Specimen No. | Material Type | Test Temp.(1) (F) | Strength, psi | | | Fracture Stress (psi) | Reduction in Area (percent) | Elongation, percent(2) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Yield | Ultimate | Fracture | | | Uniform | Total |
| JTJ | Base | RT | 65,820 | 91,120 | 58,470 | 191,000 | 69.4 | 8.6 | 21.2 |
| JTU | Base | 180 | 62,500 | 86,790 | 54,880 | 180,000 | 70.0 | 8.4 | 20.0 |
| JT3 | Base | 543 | 60,850 | 87,930 | 60,850 | 184.000 | 67.0 | 9.9 | 20.5 |
| JU6 | Weld | RT | 72,760 | 86,020 | 54,080 | 172,100 | 68.6 | 6.2 | 20.5 |
| JUJ | Weld | 543 | 57,520 | 76,020 | 49,800 | 155,100 | 68.0 | 7.1 | 22.9 |
| JY3 | Haz | RT | 70,770 | 87,270 | 52,550 | 187,000 | 72.0 | 6.8 | 19.6 |
| JYJ | Haz | 180 | 66,630 | 80,310 | 49,690 | 175,200 | 72.0 | 6.0 | 18.2 |
| JY6 | Haz | 543 | 63,520 | 84,650 | 58,130 | 166,300 | 65.0 | 6.4 | 21.6 |

(1) Room temperature (RT) is approximately 75 F.
(2) The elongation is for a 1-inch gauge length.

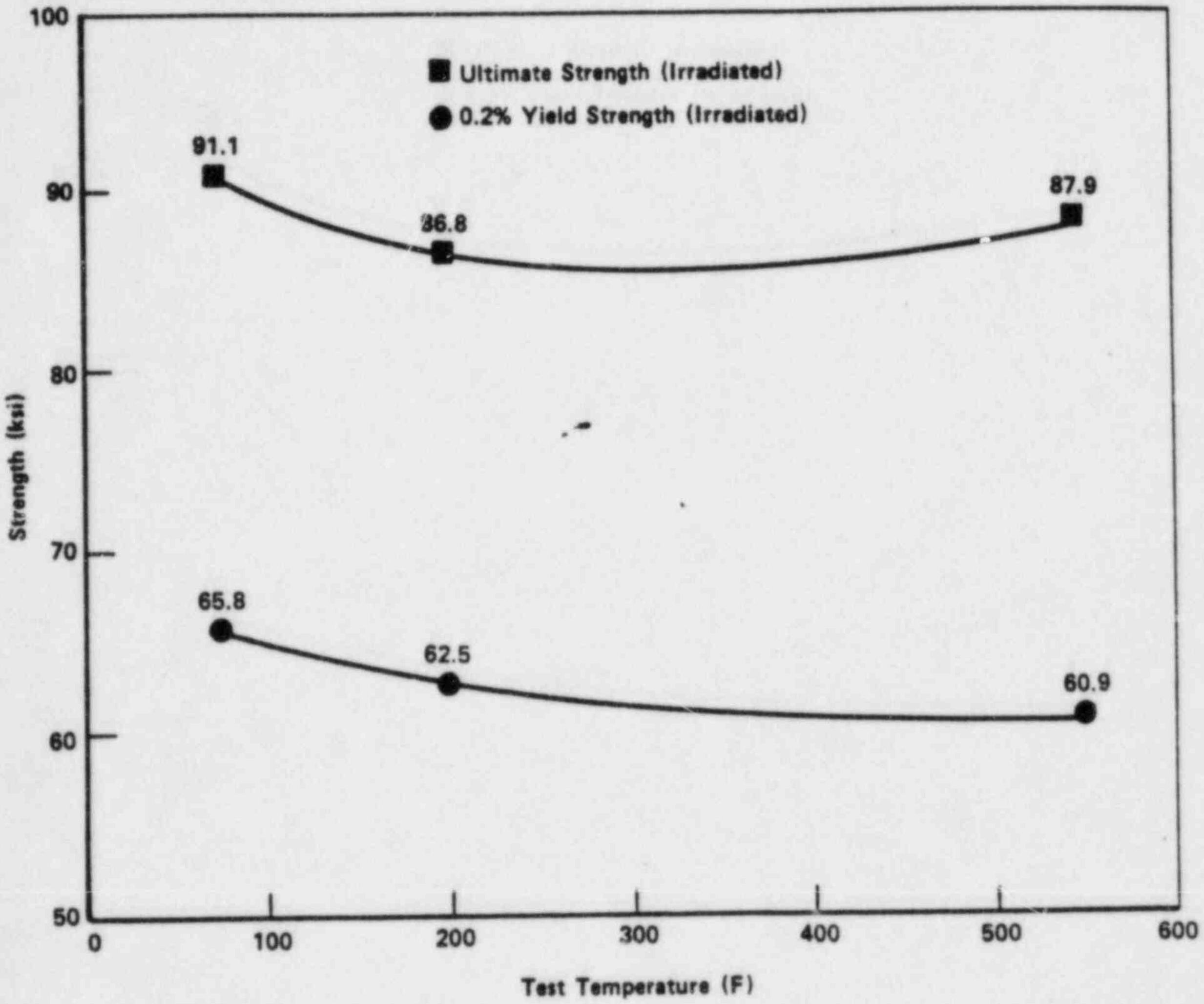


FIGURE 23. BASE METAL YIELD AND ULTIMATE TENSILE STRENGTHS VERSUS TEST TEMPERATURE FOR THE IRRADIATED TENSILE SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

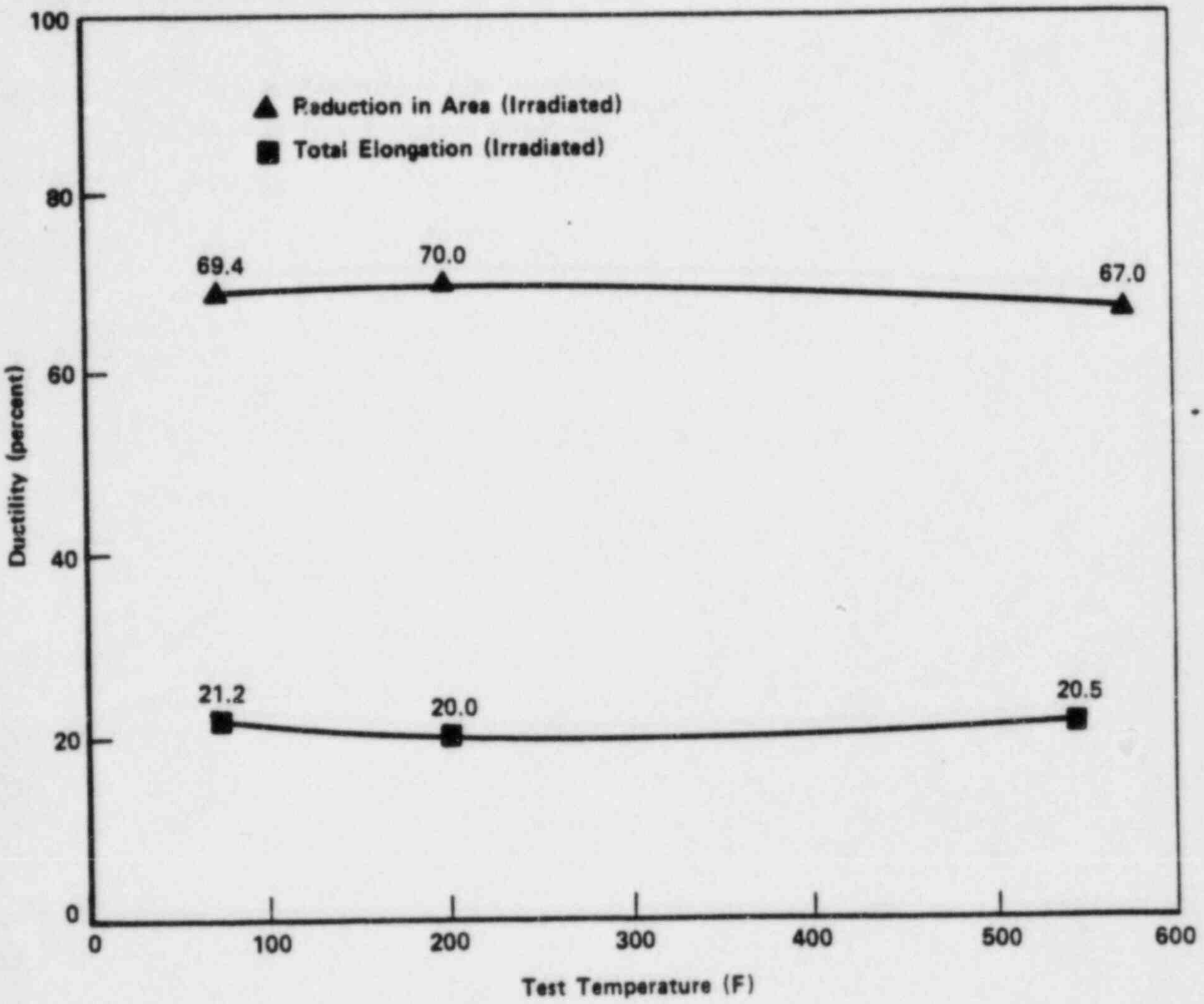
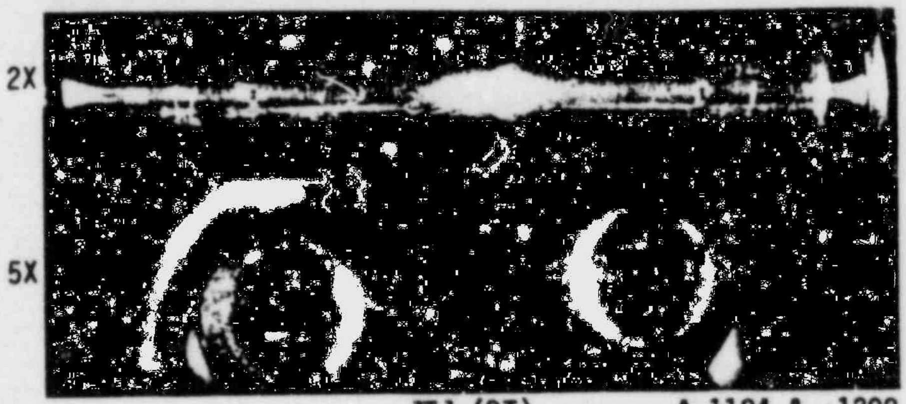
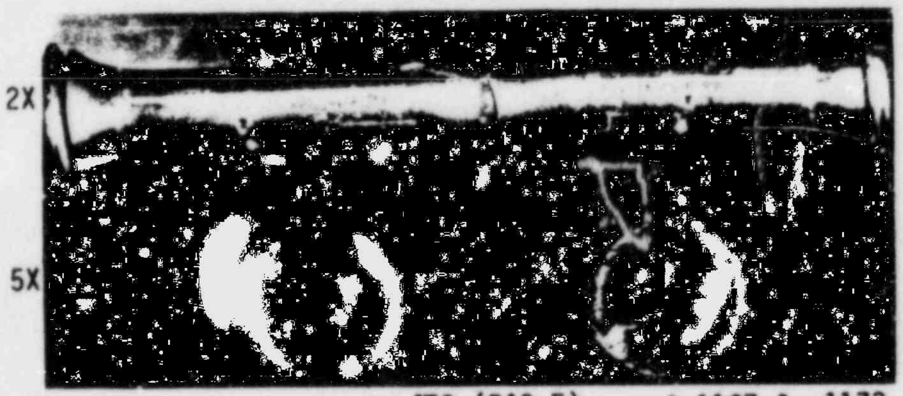


FIGURE 24. BASE METAL TOTAL ELONGATION AND REDUCTION IN AREA VERSUS TEST TEMPERATURE FOR THE IRRADIATED TENSILE SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE



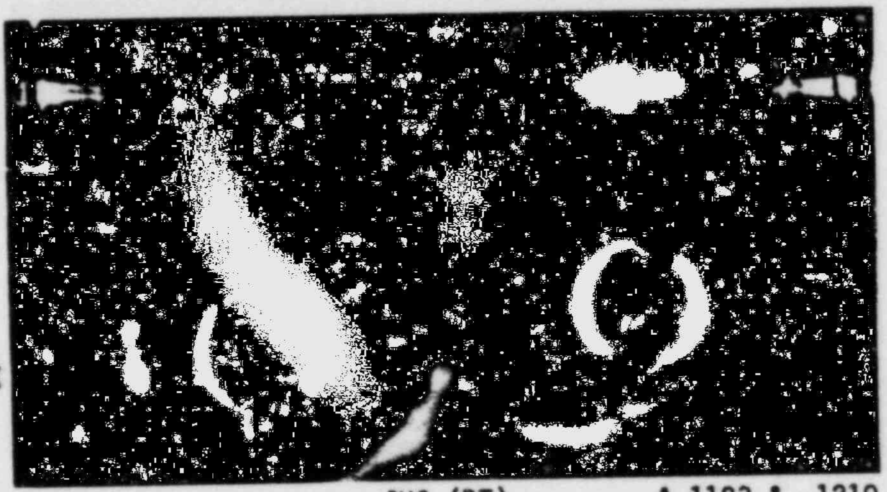
JTJ (RT) A-1184 & -1208

JTU (180 F) A-1179 & -1180

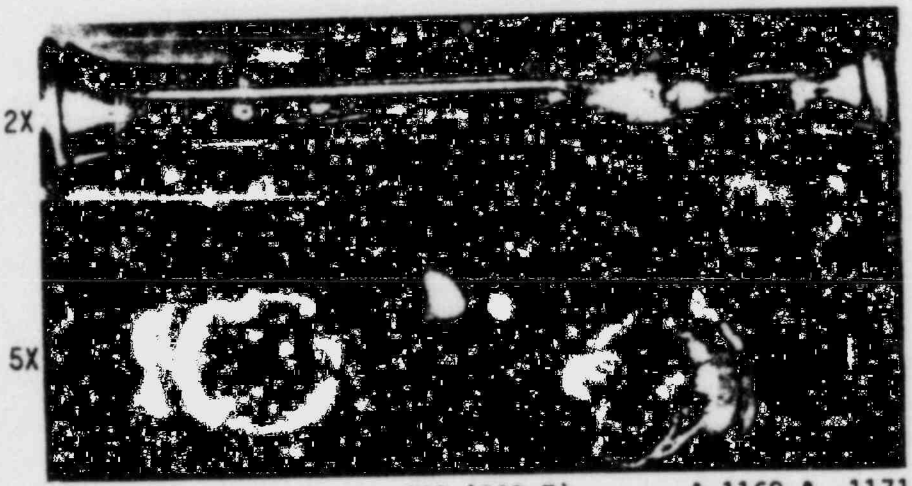


JT3 (543 F) A-1167 & -1173

FIGURE 25. POSTTEST PHOTOGRAPHS OF THE IRRADIATED BASE METAL TENSILE SPECIMENS SHOWING BOTH THE REDUCED AREAS AND FRACTURE SURFACES (VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE)

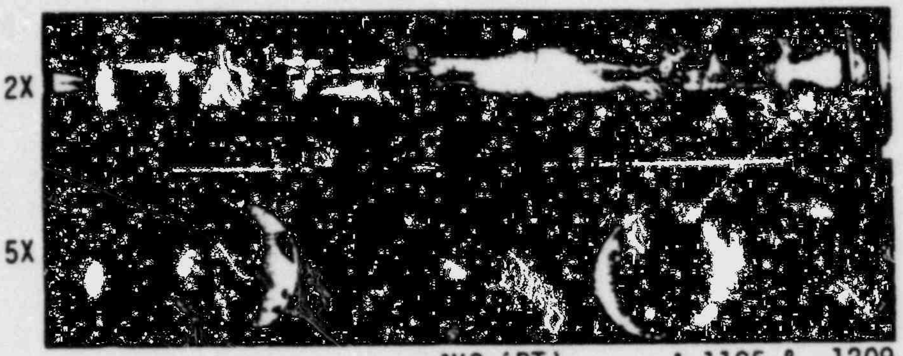


JU6 (RT) A-1183 & -1210

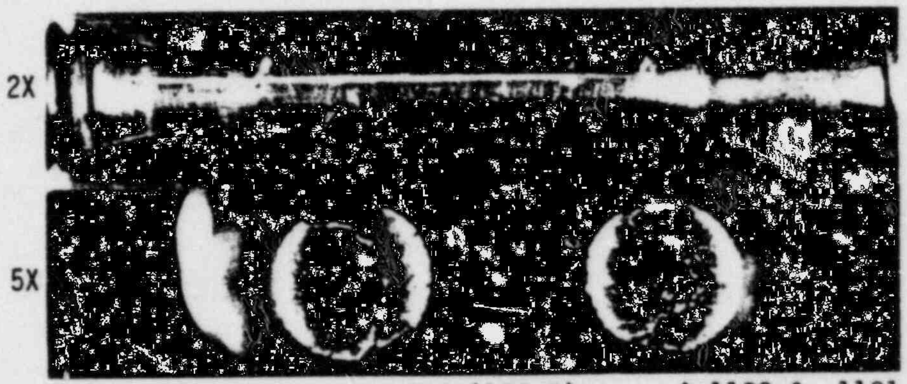


JUJ (543 F) A-1168 & -1171

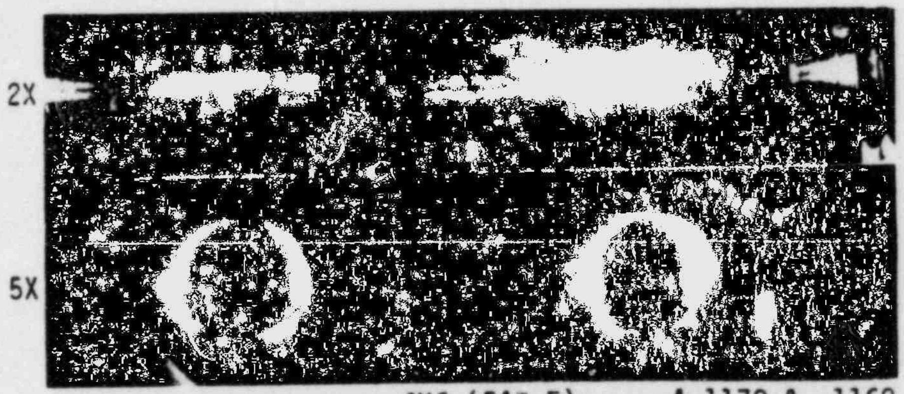
FIGURE 26. POSTTEST PHOTOGRAPHS OF THE IRRADIATED WELD METAL TENSILE SPECIMENS SHOWING BOTH THE REDUCED AREAS AND FRACTURE SURFACES (VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE)



JY3 (RT) A-1185 & -1209



JYJ (180 F) A-1182 & -1181



JY6 (543 F) A-1170 & -1169

FIGURE 27. POSTTEST PHOTOGRAPHS OF THE IRRADIATED HAZ METAL TENSILE SPECIMENS SHOWING BOTH THE REDUCED AREAS AND FRACTURE SURFACES (VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE)

These tensile data can be compared to the baseline data given in Table 13. The data compare favorably for the base, weld, and HAZ metal, indicating that there is essentially no reduction in tensile properties as a result of the neutron exposure to date.

## 6.4 Chemical Analysis

It had been known for some time that the chemical composition of a pressure vessel steel affected the extent to which material properties such as fracture and crack propagation were changed during irradiation. The Nuclear Regulatory Commission (NRC) Regulatory Guide 1.99 was issued as a guide for estimating the effect of copper, nickel, and phosphorus on the reference nil-ductility (transition) temperature ($RT_{NDT}$) as a function of fluence. In order to use this guide or to establish the copper, nickel and phosphorus content, a chemical analysis must be performed. In addition, base metal chemistry must be determined.

The method of X-ray fluorescence (XRF) was used to determine the copper (Cu), nickel (Ni), and phosphorus (P) contents of the base and weld metal specimens. Five irradiated base metal and five irradiated weld metal samples consisting of broken halves of a tested Charpy V-notch specimen were analyzed for Cu, Ni, and P content. The analytical results for the smaples are listed in Table 14.

Some Analyses were run in duplicate and the values for each run are given in Table 14. The calculated accuracy for this X-ray fluorescence chemical analysis is ± 15% for copper, ± 6.0% for nickel, and ± 10% for phosphorus. The estimated detection limit is 0.02 weight percent for copper and 0.01 weight percent for both nickel and phosphorus.

The results of samples of broken unirradiated baseline Charpy specimens were obtained earlier. These data are also shown in Table 14. The chemical analysis results of unirradiated samples reported in the October 1977 General Electric Report NEDO-21708 are also listed for comparison. All results are similar, as expected, within the error bands noted above.

## TABLE 13. TENSILE PROPERTIES OF THE UNIRRADIATED MATERIALS FOR THE VERMONT YANKEE NUCLEAR GENERATING PLANT

| Specimen No. | Material Type | Test Temp.[(a)] (F) | Strength, psi |  |  | Fracture Stress (psi) | Reduction in Area (percent) | Elongation, percent[(b)] |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  | Yield | Ultimate | Fracture |  |  | Uniform | Total |
| JT1 | Base | RT | 64,390 | 89,490 | 56,120 | 196,430 | 71.4 | 10.0 | 24.1 |
| JTD | Base | 180 | 61,910 | 84,830 | 52,950 | 184,400 | 71.3 | 8.9 | 20.0 |
| JTK | Base | 543 | 61,610 | 89,100 | 63,140 | 163,160 | 61.3 | 9.0 | 20.6 |
| JU1 | Weld | RT | 68,000 | 82,000 | 50,100 | 182,840 | 72.6 | 10.2 | 26.9 |
| JUD | Weld | 543 | 67,620 | 85,340 | 54,990 | 169,810 | 67.6 | 8.9 | 21.2 |
| JYC | HAZ | RT | 68,090 | 88,210 | 53,860 | 194,850 | 72.4 | 6.8 | 21.7 |
| JYP | HAZ | 180 | 65,620 | 83,980 | 60,850 | 156,250 | 61.0 | 6.9 | 16.7 |
| JYU | HAZ | 543 | 64,500 | 83,770 | 57,810 | 164,740 | 65.0 | 6.0 | 23.5 |

(a) Room temperature (RT) was approximately 80 F.
(b) The elongation is for a 1-inch gage length.

TABLE 14. CHEMICAL ANALYSES RESULTS FOR VERMONT YANKEE BASE AND WELD METAL SPECIMENS

| Specimen No. | Material Type | Elements, Weight Percent | | |
|---|---|---|---|---|
| | | Cu | Ni | P |
| JDD | Base (U) | 0.11 | 0.66 | 0.020 |
| JDD | Base (U) | 0.11 | 0.66 | 0.020 |
| JDE | Base (U) | 0.11 | 0.71 | 0.011 |
| JDE | Base (U) | 0.10 | 0.71 | 0.013 |
| (a) | Base (U) | 0.10 | 0.66 | 0.020 |
| JB1 | Base (I) | 0.11 | 0.68 | 0.019 |
| JB1 | Base (I) | 0.10 | 0.67 | 0.010 |
| JBK | Base (I) | 0.10 | 0.70 | 0.014 |
| JBT | Base (I) | 0.10 | 0.68 | 0.010 |
| JB3 | Base (I) | 0.10 | 0.65 | 0.010 |
| JCC | Base (I) | 0.10 | 0.66 | 0.014 |
| JCC | Base (I) | 0.10 | 0.69 | 0.010 |
| JJP | Weld (U) | 0.030 | 0.91 | 0.013 |
| JJP | Weld (U) | 0.035 | 0.93 | 0.013 |
| JKT | Weld (U) | 0.030 | 0.93 | 0.013 |
| JKT | Weld (U) | 0.030 | 0.93 | 0.010 |
| (a) | Weld (U) | 0.010 | 0.95 | 0.012 |
| JE5 | Weld (I) | 0.024 | 0.94 | 0.012 |
| JE5 | Weld (I) | 0.027 | 0.95 | 0.013 |
| JKP | Weld (I) | 0.035 | 0.88 | 0.010 |
| JEU | Weld (I) | 0.027 | 1.01 | 0.013 |
| JJL | Weld (I) | 0.027 | 1.03 | 0.023 |
| JKM | Weld (I) | 0.030 | 0.96 | 0.010 |
| JKM | Weld (I) | 0.038 | 0.93 | 0.016 |

(a) From NEDO - 21707, (U) - Unirradiated, (I) - Irradiated

## 6.5 Hardness

The Rockwell B hardness of five irradiated base metal and five irradiated weld metal specimens were measured. The hardness values obtained are given in Table 15. Also shown are the data obtained earlier on unirradiated base and weld metal specimens. Given the error band of about ± 1.0 unit, the hardness of the base metal samples is unchanged, while that for the weld metal may have decreased slightly.

# TABLE 15. ROCKWELL HARDNESS TEST RESULTS FOR VERMONT YANKEE BASE AND WELD METAL SPECIMENS

| Specimen No. | Material Type | Rockwell B Hardness | | | | | Average Hardness |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | |
| (a) | Steel | 91.2 | 91.5 | 91.7 | 91.5 | 91.5 | 91.5 ± 0.2 |
| JB4 | Base (U) | 91.2 | 91.5 | 90.6 | 92.2 | 91.1 | 91.3 ± 0.6 |
| JC1 | Base (U) | 92.0 | 91.9 | 91.5 | 91.7 | 91.7 | 91.8 ± 0.2 |
| JD2 | Base (U) | 92.0 | 91.0 | 92.7 | 92.6 | 92.1 | 92.3 ± 0.4 |
| JBB | Base (I) | 91.8 | 92.0 | 91.8 | 91.9 | 92.5 | 92.0 ± 0.2 |
| JCA | Base (I) | 92.5 | 92.0 | 92.5 | 92.5 | 91.1 | 92.1 ± 0.6 |
| JBD | Base (I) | 92.6 | 92.2 | 92.5 | 92.4 | 92.1 | 92.3 ± 0.2 |
| JE6 | Weld (U) | 92.5 | 93.0 | 91.9 | 91.0 | 92.3 | 92.1 ± 0.8 |
| JJ2 | Weld (U) | 92.5 | 93.0 | 91.9 | 91.0 | 92.3 | 92.1 ± 0.8 |
| JK1 | Weld (U) | 93.3 | 93.2 | 93.4 | 92.0 | 92.2 | 92.8 ± 0.7 |
| JJB | Weld (I) | 87.9 | 87.4 | 88.0 | 88.2 | 88.1 | 87.9 ± 0.3 |
| JJT | Weld (I) | 90.5 | 89.9 | 91.3 | 90.9 | 91.2 | 90.8 ± 0.6 |
| JJM | Weld (I) | 89.9 | 88.4 | 89.3 | 87.9 | 90.1 | 89.1 ± 0.9 |
| (a) | Steel | 91.8 | 91.8 | 91.7 | 91.8 | 92.2 | 91.9 ± 0.2 |

(a) Rockwell B Standard Test Block of hardness 91.9 ± 1.0.
(u) = Unirradiated, (I) = Irradiated.

## 7.0 CONCLUSIONS

Evaluation of the fast neutron dosimetry, chemical analysis, and mechanical property test (Charpy V-notch, tensile and hardness) results for specimens from the Vermont Yankee Nuclear Generating Plant surveillance capsule led to the following conclusions:

### Neutron Dosimetry

- The Vermont Yankee capsule and surveillance specimens at the 30-degree azimuthal location received a fast neutron fluence ($E > 0.1$ MeV) of $4.3 \times 10^{16}$ n/cm$^2$ as a result of operation from initial startup to March 1983 (7.54 EFPY).
- The Vermont Yankee pressure vessel azimuthal fluence (or flux) varied by as much as a factor of 2. The maximum fast neutron exposure occurred at about the 0-degree azimuthal position and the lead factor was 0.83 for the pressure vessel inside surface, 1.13 for the 1/4 T, and 2.89 for the 3/4 T positions.
- The maximum fast neutron fluence ($E > 1.0$ MeV) at the pressure vessel 1/4 T position was $3.8 \times 10^{16}$ n/cm$^2$ as a result of operation from initial startup to March 1983 (7.54 EFPY).
- Extrapolating the present data to the end of life (EOL) of 32 equivalent full power years (EFPY), the maximum calculated EOL fast neutron fluence ($E > 1.0$ MeV) at the pressure vessel 1/4 T position would be $1.61 \times 10^{17}$ n/cm$^2$. If a 20 percent accuracy is assumed, the upper bound of the maximum EOL fast neutron fluence ($E > 1.0$ MeV) at the pressure vessel 1/4 T position would be $1.9 \times 10^{17}$ n/cm$^2$.

- The EOL projected maximum fast neutron fluence (E > 1.0 MeV) of 2.2 x $10^{17}$ n/cm$^2$ at the pressure vessel surface agrees well with the value of between 2.0 and 2.9 x $10^{17}$ n/cm$^2$ predicted by the Southwest Research Institute.

## Charpy

- After a fast neutron fluence (E > 1.0 MeV) of 4.3 x $10^{16}$ n/cm$^2$, the irradiated Charpy V-notch specimens from the Vermont Yankee 30-degree surveillance capsule indicate a base metal upper shelf energy of 128 ft-lb, a weld metal upper shelf energy of 122 ft-lb, and a HAZ metal upper shelf energy of 117 ft-lb. These values were sightly higher than those obtained with the unirradiated baseline materials, except for the base metal which dropped 20 ft-lb. However, these values are still well above the minimum allowable upper shelf energy of 50 ft-lb specified in 10 CFR 50 Appendix G.

## Tensile

- All tensile test specimens exhibited ductile failures as evidenced by the cup-and-cone type fracture shape. The tensile properties were essentially the same as those obtained for the unirradiated baseline materials.

## Chemistry

- The copper, nickel, and phosphorus content obtained at BCL for both unirradiated baseline and irradiated specimens compare well (within about 15 percent) to the content reported in NEDO-21708 except for the copper content in the weld metal and the phosphorus in some of the base and weld metal specimens.
- A comparison of the Vermont Yankee copper (Cu), nickel (Ni), and phosphorus (P) content to other BWR reactor pressure vessel base and weld metals reported in NEDO-21708 shows:

  (1) The Vermont Yankee Cu content is the lowest for both base and weld metals,
  (2) The Vermont Yankee Ni content is the highest for weld metal and in the mid range for the base metal,
  (3) The Vermont Yankee P content is the lowest for the weld metal and about in the mid range for the base metal

- Based on copper content, the base metal is the limiting material and, using the NRC Regulatory Guide 1.99, the projected shift in reference nil-ductility transition temperature for a fluence of $5 \times 10^{17}$ $n/cm^2$ will be relatively low at less than 100 F.

## Hardness

- The hardness of base and weld metal samples were essentially unchanged as a result of the exposure.

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# APPENDIX A

## INSTRUMENTED CHARPY EXAMINATION

# APPENDIX A

## INSTRUMENTED CHARPY EXAMINATION

### INTRODUCTION

The radiation-induced embrittlement of the pressure vessel of a commercial nuclear reactor is monitored by evaluation of Charpy V-notch impact specimens in surveillance capsules. In a conventional Charpy V-notch impact test, the information obtained for each specimen includes the absorbed energy, the lateral expansion, and the fracture appearance. Curves of energy versus temperature and lateral expansion versus temperature can be drawn for a series of specimens of a given irradiated material tested over a range of temperature. These curves, when compared to similar curves for the unirradiated material, show the shift in behavior due to irradiation.

Information in addition to the energy absorbed can be determined from a Charpy V-notch impact test by instrumenting the equipment used to perform the test. The loads during impact are obtained by instrumenting the Charpy striker or tup with strain gages, so that the striker is essentially a load cell. The details of this technique have been reported previously(1,2,3).

The additional information obtained from the instrumented Charpy test includes the general yield load ($P_{GY}$) (plastic yielding across the entire cross section of the Charpy specimen), the maximum load ($P_{max}$), and the crack arrest load. In addition, if brittle fracture occurs, the brittle fracture load ($P_F$), and the time to brittle fracture can be obtained (see Figure A-1). The area under the load-time curve corresponds to the total energy absorbed, which is the only data obtained in a normal uninstrumented Charpy test. The instrumented test, however, allows separation of the energy abosrbed into (1) the energy required for crack initiation (approximated by the premaximum load energy), (2) the energy required for ductile tearing (postmaximum load

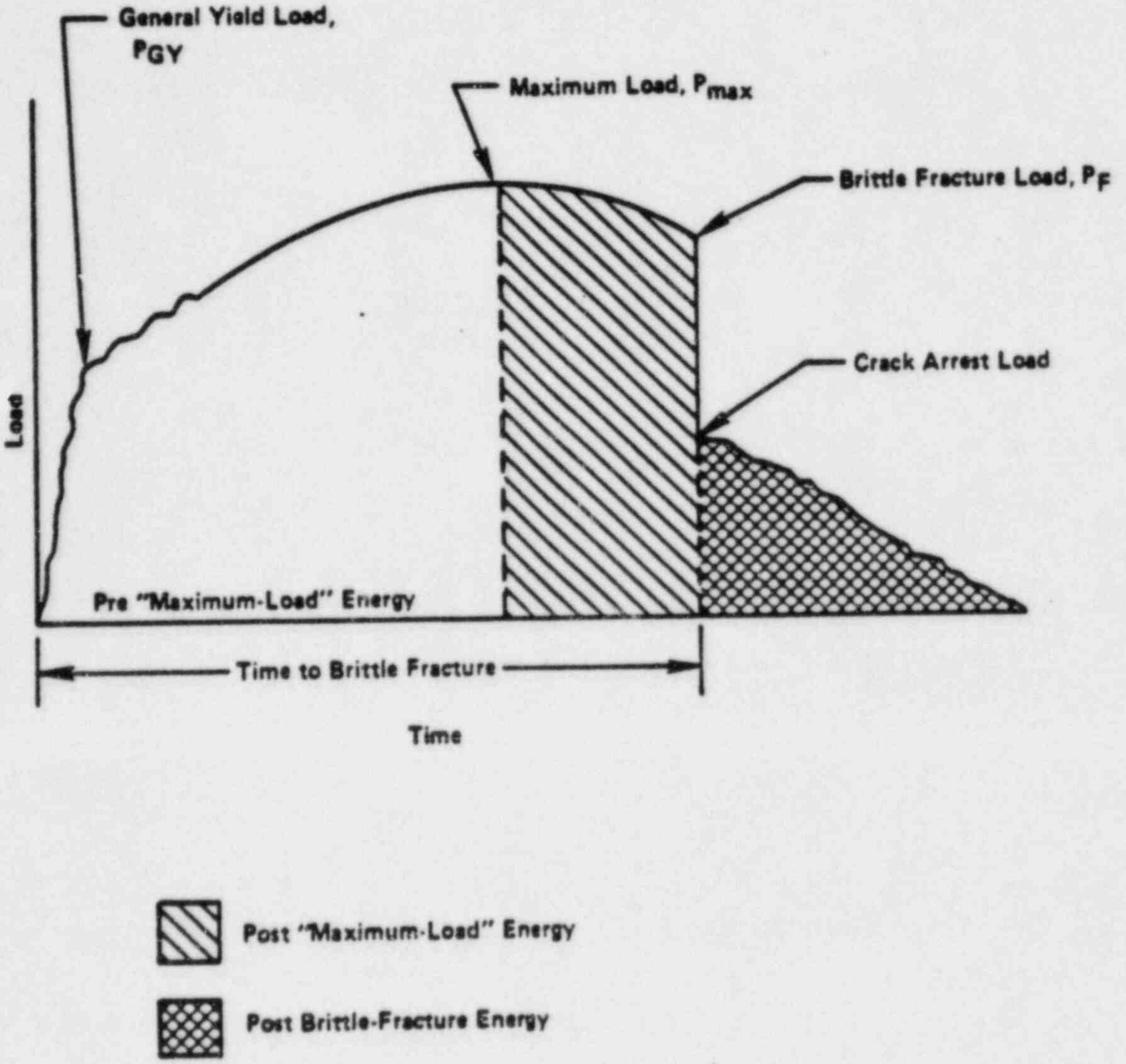


FIGURE A-1. AN IDEALIZED LOAD-TIME HISTORY FOR A CHARPY IMPACT TEST energy), and (3) the energy associated with shear lip formation (postbrittle fracture energy), as shown in Figure A-1. Material properties, such as the yield strength and flow strength, appropriate to the loading rate of the Charpy impact test, may be subsequently calculated from the load information obtained by instrumenting the Charpy test(4). This information enhances the value of the relatively small Charpy specimens to reactor vessel surveillance programs. These procedures have received the endorsement of the technical community(5).

The instrumented Charpy test also gives the information shown in Figure A-1 as a function of temperature, as shown by the example in Figure A-2. Various investigators(5-8) have developed theories that permit a detailed analysis of the load-temperature diagram. This diagram can be divided into four regions of fracture behavior, as shown in Figure A-2. In each region, different fracture parameters are involved(1). The temperature corresponding to the intersection of the maximum or failure load curve and that of the general yield load in Figure A-2 is the temperature at which fracture occurs upon general yielding. Extended discussions of these fracture parameters can be found in the references indicated above.

## EXPERIMENTAL PROCEDURES

The general procedures for the instrumented Charpy test are the same as those for the conventional impact test, and are described in the main text of this report. The additional data are obtained through a fairly simple electronic configuration, as shown in the schematic diagram of Figure A-3.

The striker of the impact machine is modified to make it a dynamic load sensor. The modification consists of a four-arm resistance strain gage bridge positioned on the striker to detect the compression loading of the striker during the impact loading of the specimen. The compressive elastic strain signal resulting from the striker contacting the specimen is conditioned by a high-gain dynamic amplifier and the output is fed into a digital oscilloscope. The load-time information is digitized and displayed on the

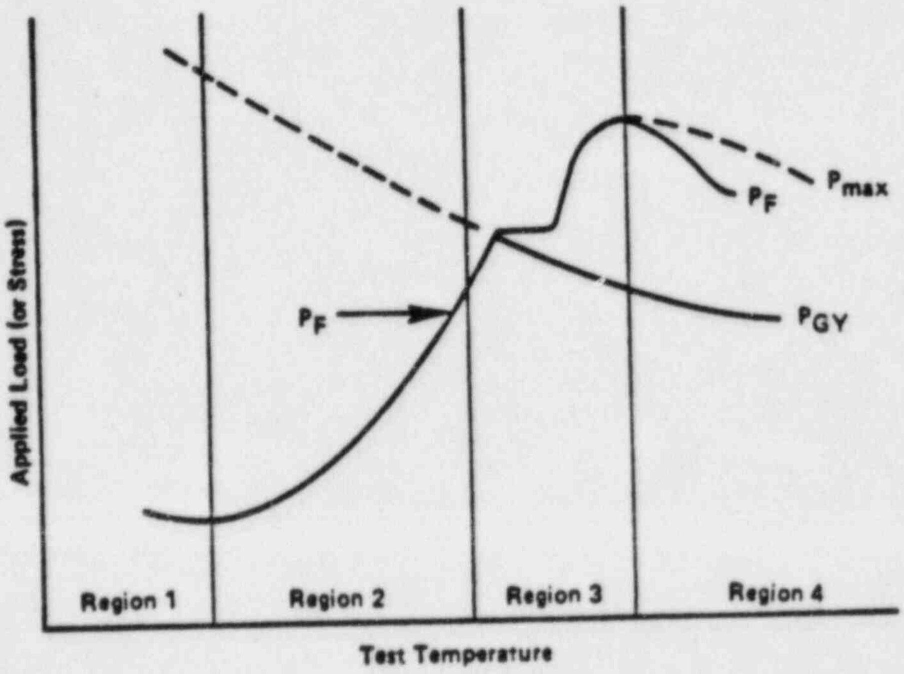


FIGURE A-2. GRAPHICAL ANALYSIS OF CHARPY IMPACT DATA

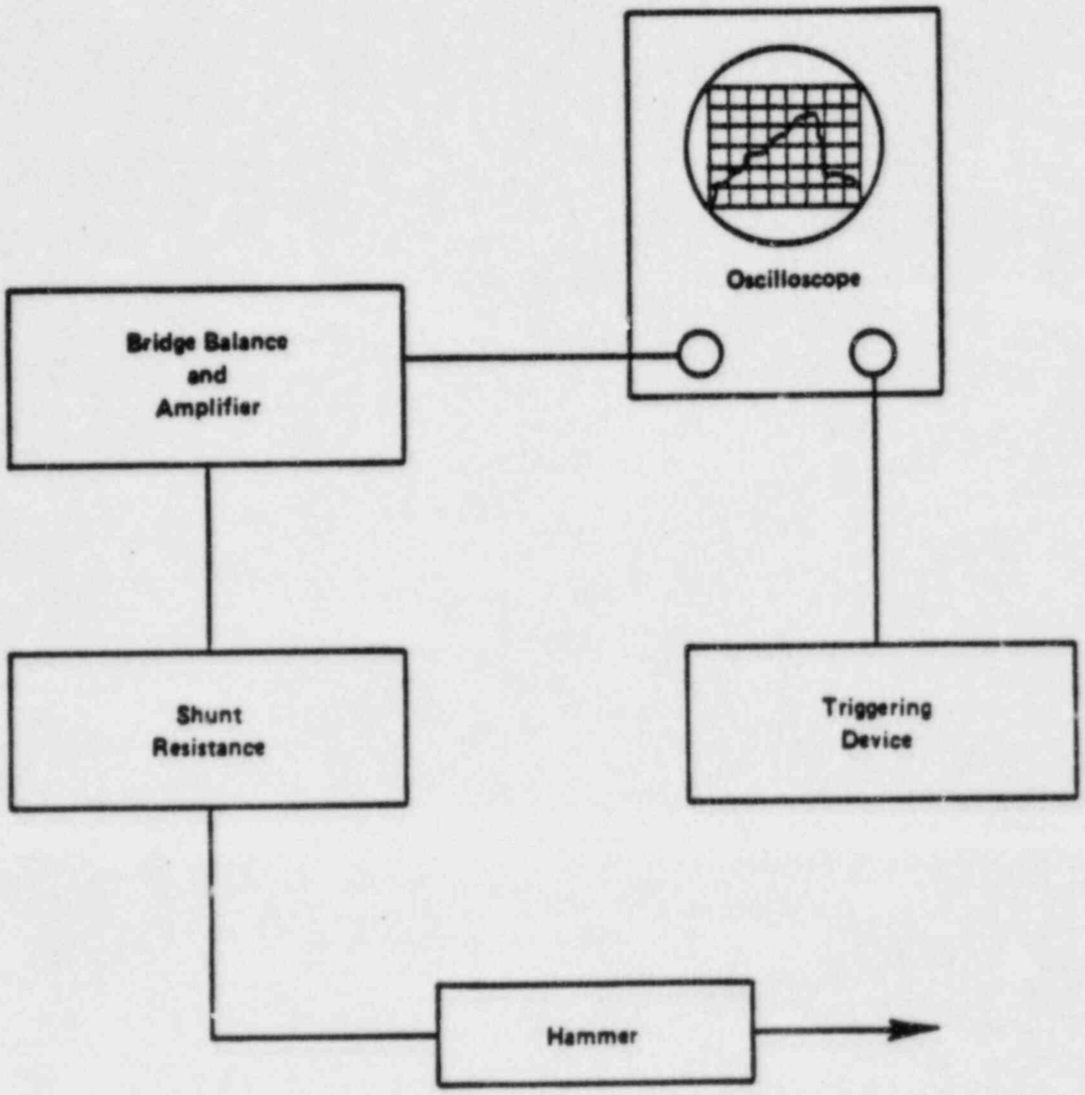


FIGURE A-3. DIAGRAM OF INSTRUMENTATION ASSOCIATED WITH INSTRUMENTED CHARPY EXAMINATION screen of the digital oscilloscope. It is subsequently plotted on an X-Y recorder. The load-time history as a function of test temperature forms the basis for further data analysis. The digital oscilloscope is triggered by a light beam device at the correct time to capture the amplifier output signal(3,4).

## RESULTS AND DISCUSSIONS

Specimens of three materials were tested. These materials were base metal (longitudinal orientation), weld metal, and heat-affected zone (HAZ) material. The instrumented Charpy results are presented in Tables A-1 through A-3. The tables list the specimen number, test temperature, impact energy, general yield load, maximum load, brittle fracture load, and crack arrest load. The load time curves are presented in Figures A-4 through A-6. It can readily be observed that the features of the load-time curves change as a function of temperature. The energy values listed in the tables are those obtained from the impact machine dial. Each curve falls into one of the six distinctive notch-bar bending classifications shown in Figure A-7. The pertinent data used in the analysis of each record are the general yield load ($P_{GY}$), the maximum load ($P_{max}$), the fast (brittle) fracture load ($P_F$), and the arrest load. The load-temperature curves obtained for the three materials are shown in Figures A-8 through A-11.

TABLE A-1. INSTRUMENTED CHARPY IMPACT RESULTS FOR THE IRRADIATED BASE METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

(The energy values listed are obtained from the impact machine dial.)

| Specimen Identification | Test Temperature, F | Impact Energy, ft-lb | General Yield Load $P_{GY}$, lb | Maximum Load $P_{max}$, lb | Fast Fracture Load, lb | Arrest Load, lb |
|---|---|---|---|---|---|---|
| JB1 | 0 | 12.5 | 3072 | 3382 | 3380 | 240 |
| JBK | 10 | 28.0 | 3012 | 3946 | 3946 | 46 |
| JBT | 20 | 17.5 | 2960 | 3432 | 3386 | 168 |
| JB3 | 20 | 32.0 | 2912 | 4050 | 4048 | 78 |
| JCC | 40 | 35.0 | 2908 | 4056 | 4054 | 100 |
| JD1 | 50 | 50.5 | 2850 | 4096 | 4086 | 216 |
| JBB | 60 | 54.0 | 2716 | 4084 | 4048 | 496 |
| JBJ | 80 | 76.0 | 2800 | 4076 | 3916 | 1630 |
| JBD | 120 | 92.0 | 2494 | 4098 | 3520 | 1882 |
| JCA | 160 | 124.0 | 2540 | 3924 | N/A | N/A |
| JDJ | 240 | 127.0 | 2352 | 3762 | N/A | N/A |
| JC5 | 320 | 128.0 | 2443 | 3780 | N/A | N/A |

TABLE A-2. INSTRUMENTED CHARPY IMPACT RESULTS FOR THE IRRADIATED WELD METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

(The energy values listed are obtained from the impact machine dial.)

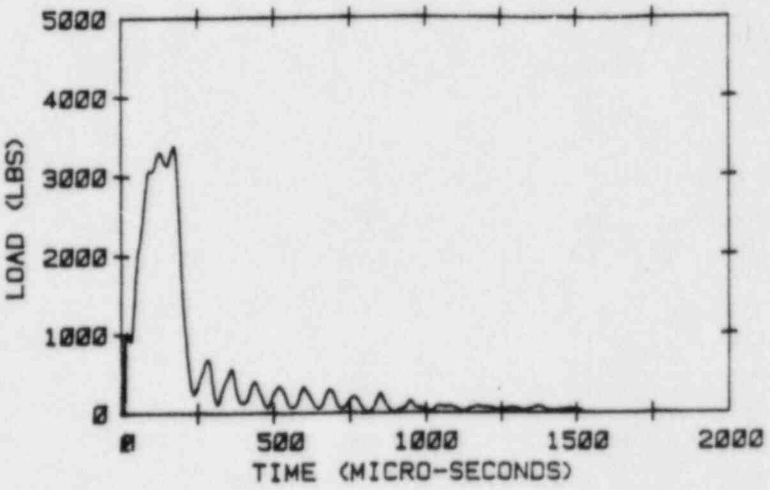
| Specimen Identification | Test Temperature, F | Impact Energy, ft-lb | General Yield Load $P_{GY}$, lb | Maximum Load $P_{max}$, lb | Fast Fracture Load, lb | Arrest Load, lb |
|---|---|---|---|---|---|---|
| JE5 | -80 | 28.0 | 3376 | 4094 | 4092 | 54 |
| JKP | -40 | 29.0 | 3280 | 4036 | 4026 | 444 |
| JEU | -30 | 44.0 | 3470 | 3930 | 3826 | 438 |
| JJL | -20 | 49.0 | 3176 | 4006 | 3872 | 544 |
| JKM | 0 | 30.0 | 3136 | 3984 | 3982 | 702 |
| JJT | 0 | 55.5 | 3058 | 3914 | 3736 | 1136 |
| JJ7 | 19 | 67.0 | 3090 | 4006 | 3740 | 1458 |
| JJB | 40 | 68.5 | 2956 | 3862 | 3586 | 1798 |
| JKE | 80 | 99.0 | 2914 | 3924 | 3114 | 1982 |
| JEC | 160 | 120.5 | 2652 | 3676 | N/A | N/A |
| JJ3 | 240 | 121.0 | 2438 | 3510 | N/A | N/A |
| JJM | 320 | 114.5 | 2386 | 3420 | N/A | N/A |

TABLE A-3. INSTRUMENTED CHARPY IMPACT RESULTS FOR THE IRRADIATED HAZ METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

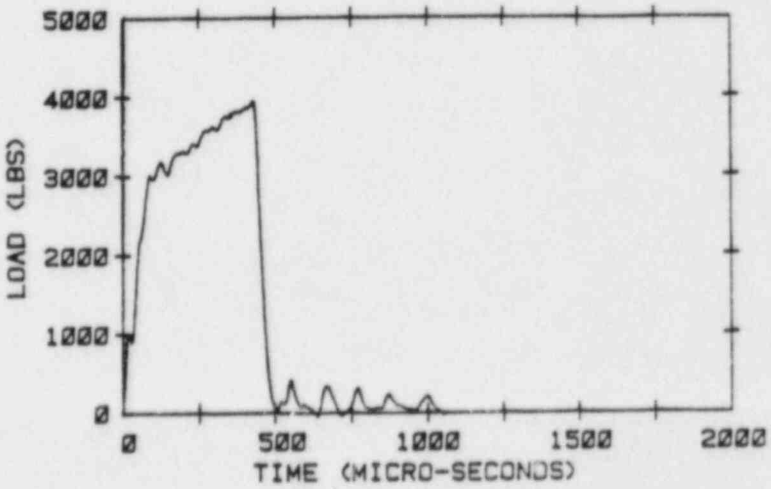
(The energy values listed are obtained from the impact machine dial.)

| Specimen Identification | Test Temperature, F | Impact Energy, ft-lb | General Yield Load $P_{GY}$, lb | Maximum Load $P_{max}$, lb | Fast Fracture Load, lb | Arrest Load, lb |
|---|---|---|---|---|---|---|
| JPA | -80 | 11.5 | 3374 | 3788 | 3780 | 122 |
| JP3 | -40 | 23.0 | 3276 | 4006 | 3990 | 42 |
| JL7 | -20 | 63.5 | 3174 | 4182 | 4082 | 1976 |
| JLT | -20 | 12.5 | 3254 | 3468 | 3454 | 602 |
| JP6 | 0 | 15.0 | 3184 | 3576 | 3564 | 616 |
| JP2 | 0 | 45.5 | 3132 | 4070 | 3996 | 1468 |
| JLD | 20 | 40.5 | 3164 | 3926 | 3868 | 1376 |
| JPB | 40 | 70.5 | 3048 | 4030 | 3938 | 2224 |
| JP4 | 80 | 56.5 | 3090 | 3832 | 3744 | 2596 |
| JM6 | 160 | 105.5 | 2804 | 4008 | N/A | N/A |
| JPC | 240 | 116.0 | 2836 | 3900 | N/A | N/A |
| JMD | 320 | 112.5 | 2644 | 3622 | N/A | N/A |

SPECIMEN NO. : JB1
TEST TEMPERATURE (F) : 0
DIAL ENERGY, (FT-LBS) : 12.5
GENERAL YIELD LOAD (LB) : 3072
MAXIMUM LOAD (LB) : 3382
FAST FRACTURE LOAD (LB) : 3380
ARREST LOAD (LB) : 240



SPECIMEN NO. : JBK
TEST TEMPERATURE (F) : 10
DIAL ENERGY, (FT-LBS) : 28
GENERAL YIELD LOAD (LB) : 3012
MAXIMUM LOAD (LB) : 3946
FAST FRACTURE LOAD (LB) : 3946
ARREST LOAD (LB) : 46



SPECIMEN NO. : JBT
TEST TEMPERATURE (F) : 20
DIAL ENERGY, (FT-LBS) : 17.5
GENERAL YIELD LOAD (LB) : 2960
MAXIMUM LOAD (LB) : 3432
FAST FRACTURE LOAD (LB) : 3386
ARREST LOAD (LB) : 168

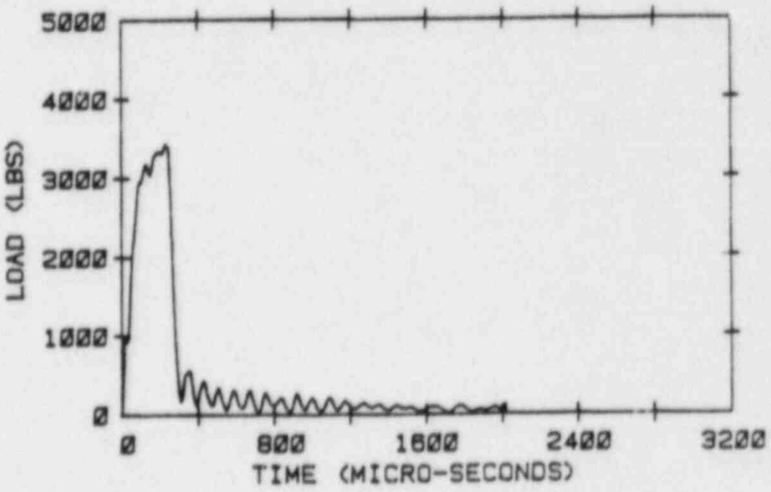
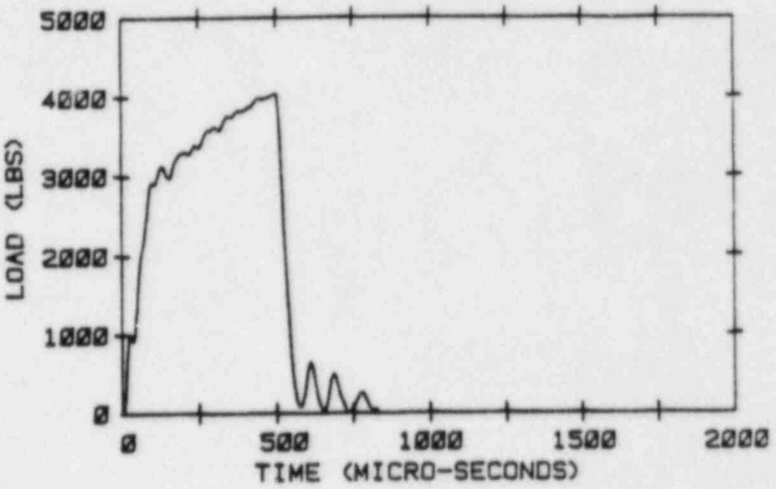
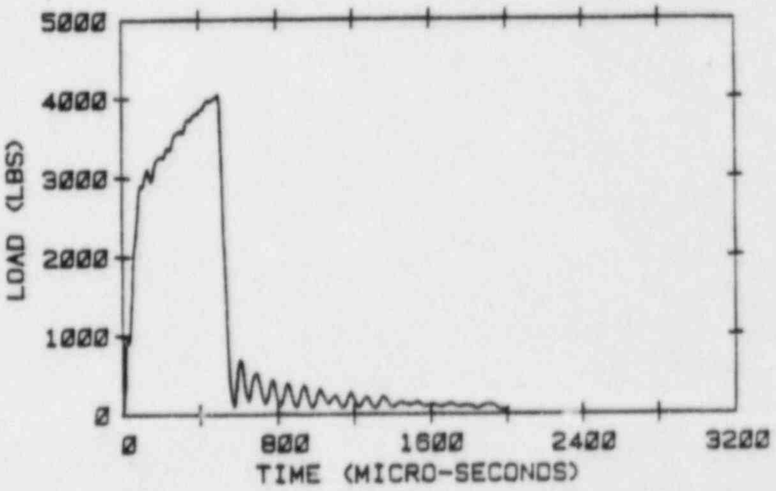


FIGURE A-4. INSTRUMENTED CHARPY IMPACT DATA FOR IRRADIATED BASE METAL (LONGITUDINAL) SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

SPECIMEN NO. : JB3
TEST TEMPERATURE (F) : 20
DIAL ENERGY, (FT-LBS) : 32
GENERAL YIELD LOAD (LB) : 2912
MAXIMUM LOAD (LB) : 4050
FAST FRACTURE LOAD (LB) : 4048
ARREST LOAD (LB) : 78



SPECIMEN NO. : JCC
TEST TEMPERATURE (F) : 40
DIAL ENERGY, (FT-LBS) : 35
GENERAL YIELD LOAD (LB) : 2908
MAXIMUM LOAD (LB) : 4056
FAST FRACTURE LOAD (LB) : 4054
ARREST LOAD (LB) : 100



SPECIMEN NO. : JD1
TEST TEMPERATURE (F) : 50
DIAL ENERGY, (FT-LBS) : 50.5
GENERAL YIELD LOAD (LB) : 2850
MAXIMUM LOAD (LB) : 4096
FAST FRACTURE LOAD (LB) : 4086
ARREST LOAD (LB) : 216

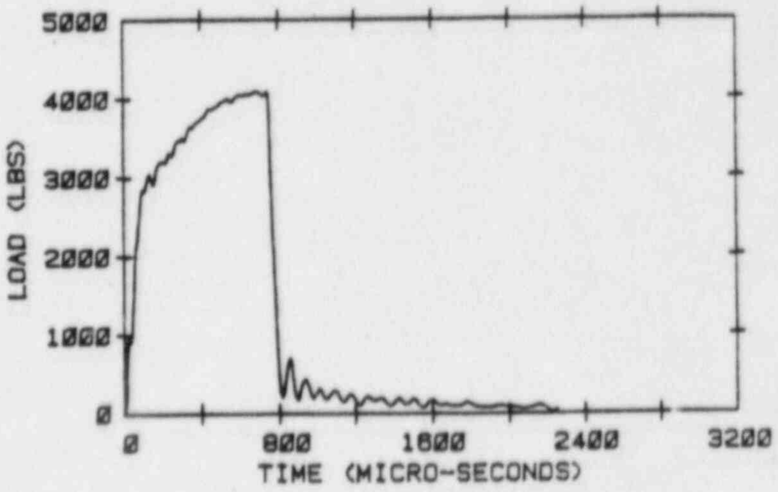
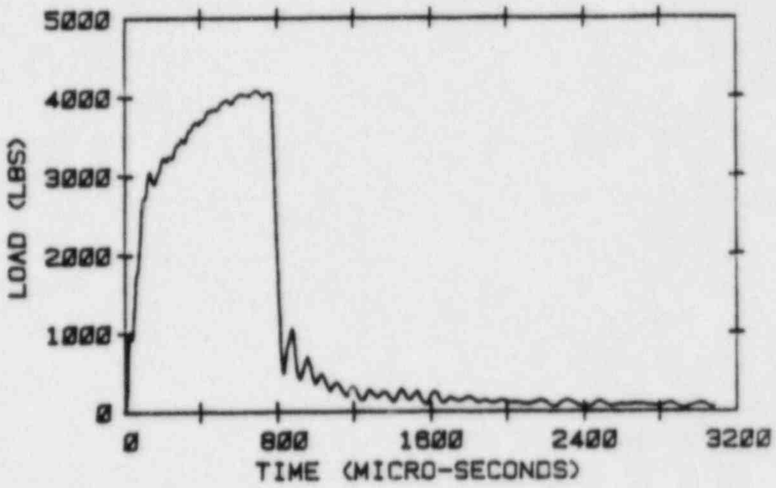
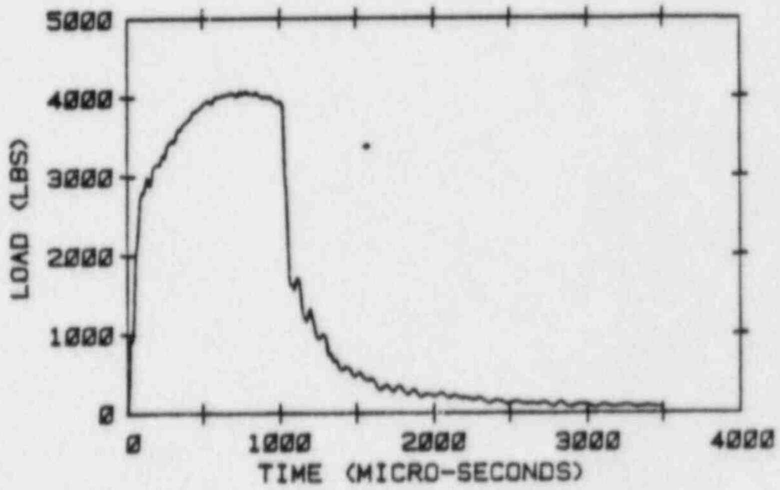


FIGURE A-4. (Continued)

SPECIMEN NO. : JBB
TEST TEMPERATURE (F) : 60
DIAL ENERGY, (FT-LBS) : 54
GENERAL YIELD LOAD (LB) : 2716
MAXIMUM LOAD (LB) : 4084
FAST FRACTURE LOAD (LB) : 4048
ARREST LOAD (LB) : 496



SPECIMEN NO. : JBJ
TEST TEMPERATURE (F) : 80
DIAL ENERGY, (FT-LBS) : 76
GENERAL YIELD LOAD (LB) : 2800
MAXIMUM LOAD (LB) : 4076
FAST FRACTURE LOAD (LB) : 3916
ARREST LOAD (LB) : 1630



SPECIMEN NO. : JBD
TEST TEMPERATURE (F) : 120
DIAL ENERGY, (FT-LBS) : 92
GENERAL YIELD LOAD (LB) : 2494
MAXIMUM LOAD (LB) : 4048
FAST FRACTURE LOAD (LB) : 3520
ARREST LOAD (LB) : 1882

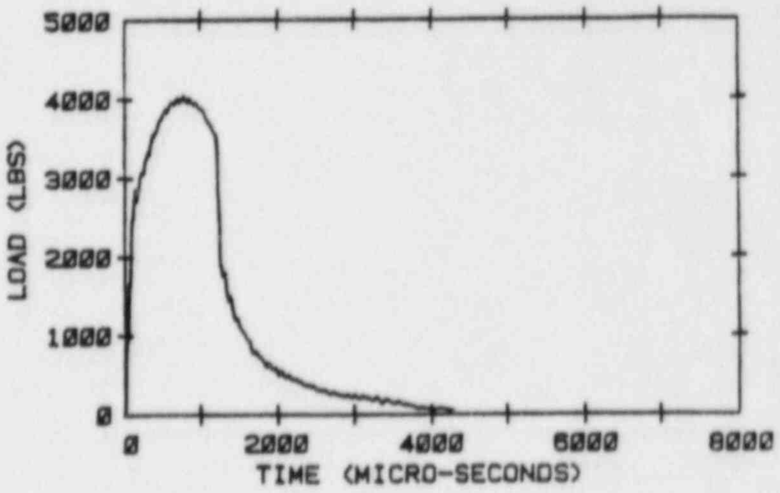
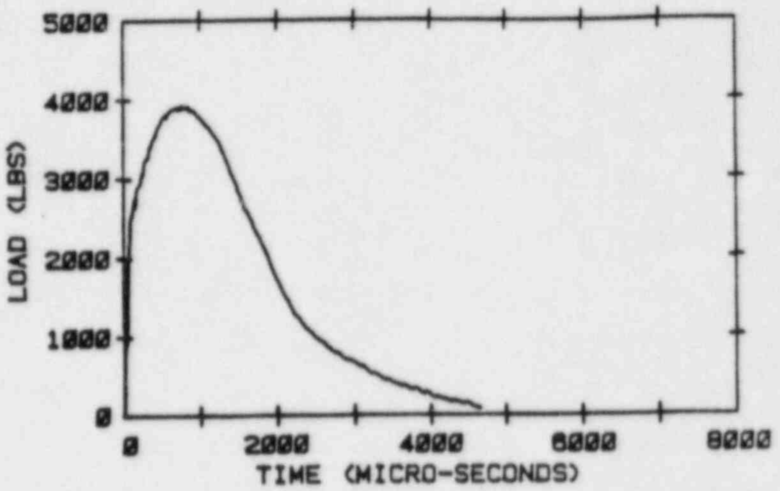
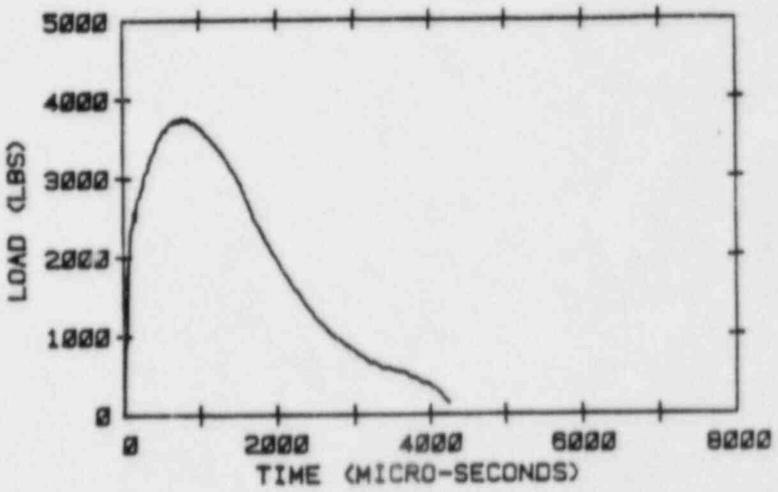


FIGURE A-4. (Continued)

SPECIMEN NO. : JCA
TEST TEMPERATURE (F) : 160
DIAL ENERGY, (FT-LBS) : 124
GENERAL YIELD LOAD (LB) : 2540
MAXIMUM LOAD (LB) : 3924
FAST FRACTURE LOAD (LB) : N/A
ARREST LOAD (LB) : N/A



SPECIMEN NO. : JDJ
TEST TEMPERATURE (F) : 240
DIAL ENERGY, (FT-LBS) : 127
GENERAL YIELD LOAD (LB) : 2362
MAXIMUM LOAD (LB) : 3762
FAST FRACTURE LOAD (LB) : N/A
ARREST LOAD (LB) : N/A



SPECIMEN NO. : JC5
TEST TEMPERATURE (F) : 320
DIAL ENERGY, (FT-LBS) : 128
GENERAL YIELD LOAD (LB) : 2348
MAXIMUM LOAD (LB) : 3780
FAST FRACTURE LOAD (LB) : N/A
ARREST LOAD (LB) : N/A

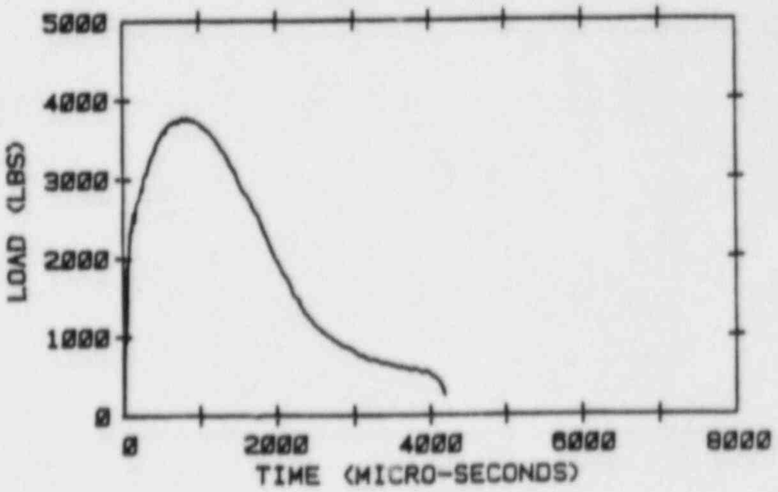
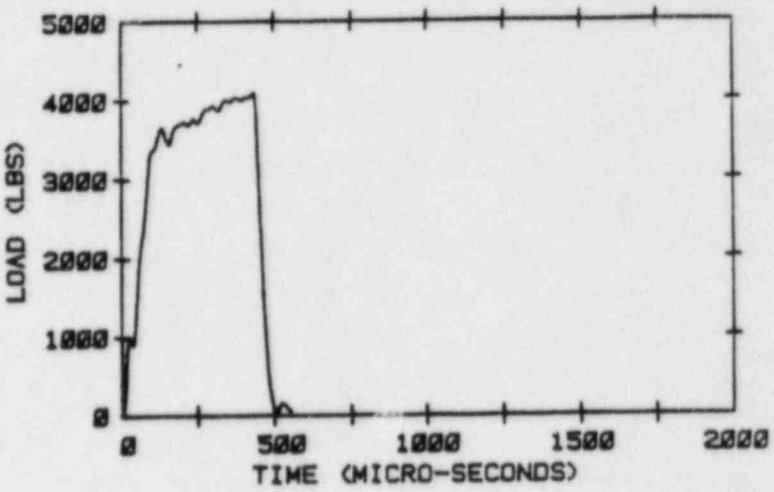
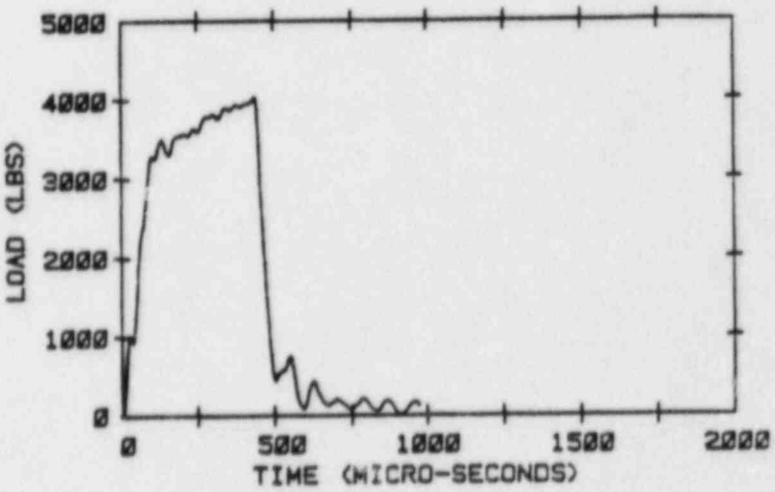


FIGURE A-4. (Concluded)

SPECIMEN NO. : JE5
TEST TEMPERATURE (F) : -80
DIAL ENERGY, (FT-LBS) : 28
GENERAL YIELD LOAD (LB) : 3378
MAXIMUM LOAD (LB) : 4094
FAST FRACTURE LOAD (LB) : 4092
ARREST LOAD (LB) : 54



SPECIMEN NO. : JKP
TEST TEMPERATURE (F) : -40
DIAL ENERGY, (FT-LBS) : 29
GENERAL YIELD LOAD (LB) : 3280
MAXIMUM LOAD (LB) : 4036
FAST FRACTURE LOAD (LB) : 4026
ARREST LOAD (LB) : 444



SPECIMEN NO. : JEU
TEST TEMPERATURE (F) : -30
DIAL ENERGY, (FT-LBS) : 44
GENERAL YIELD LOAD (LB) : 3470
MAXIMUM LOAD (LB) : 3930
FAST FRACTURE LOAD (LB) : 3826
ARREST LOAD (LB) : 438

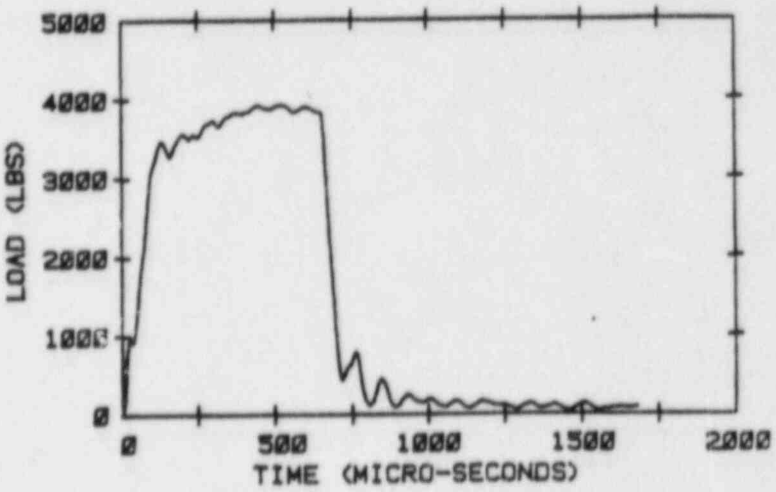
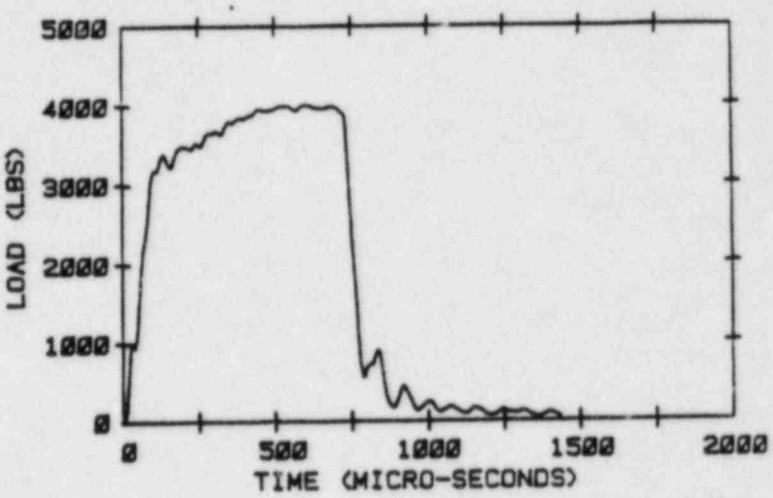
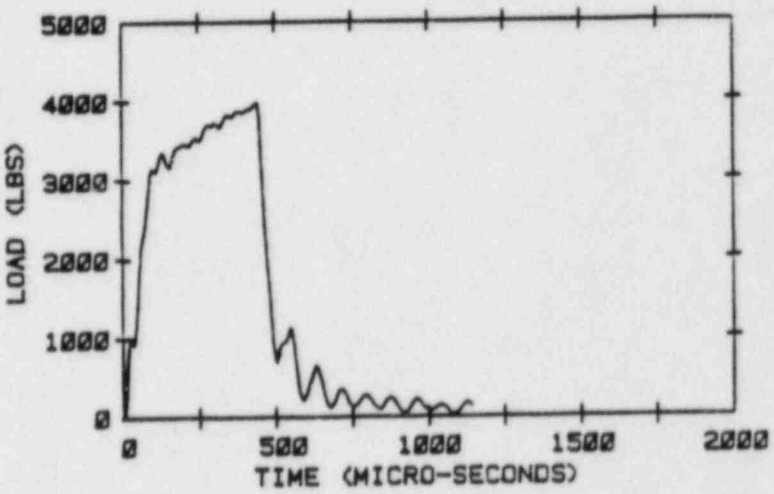


FIGURE A-5. INSTRUMENTED CHARPY IMPACT DATA FOR IRRADIATED WELD METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

SPECIMEN NO. : JJL
TEST TEMPERATURE (F) : -20
DIAL ENERGY, (FT-LBS) : 49
GENERAL YIELD LOAD (LB) : 3176
MAXIMUM LOAD (LB) : 4006
FAST FRACTURE LOAD (LB) : 3872
ARREST LOAD (LB) : 544



SPECIMEN NO. : JKM
TEST TEMPERATURE (F) : 0
DIAL ENERGY, (FT-LBS) : 30
GENERAL YIELD LOAD (LB) : 3136
MAXIMUM LOAD (LB) : 3984
FAST FRACTURE LOAD (LB) : 3982
ARREST LOAD (LB) : 702



SPECIMEN NO. : JJT
TEST TEMPERATURE (F) : 0
DIAL ENERGY, (FT-LBS) : 55.5
GENERAL YIELD LOAD (LB) : 3058
MAXIMUM LOAD (LB) : 3914
FAST FRACTURE LOAD (LB) : 3736
ARREST LOAD (LB) : 1136

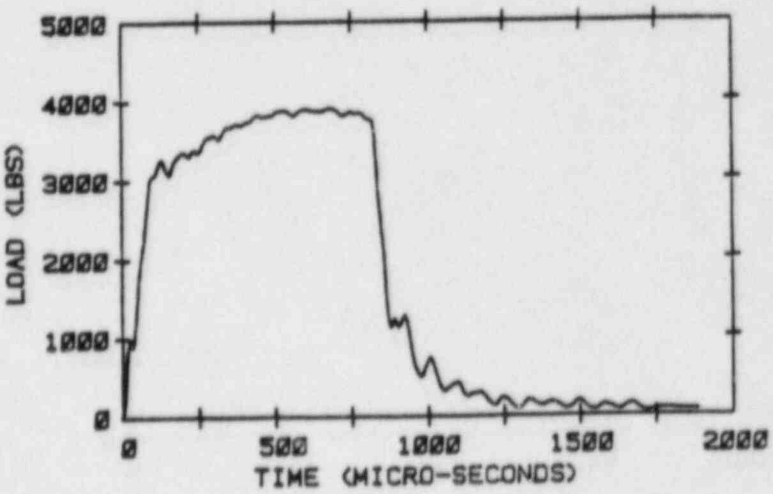
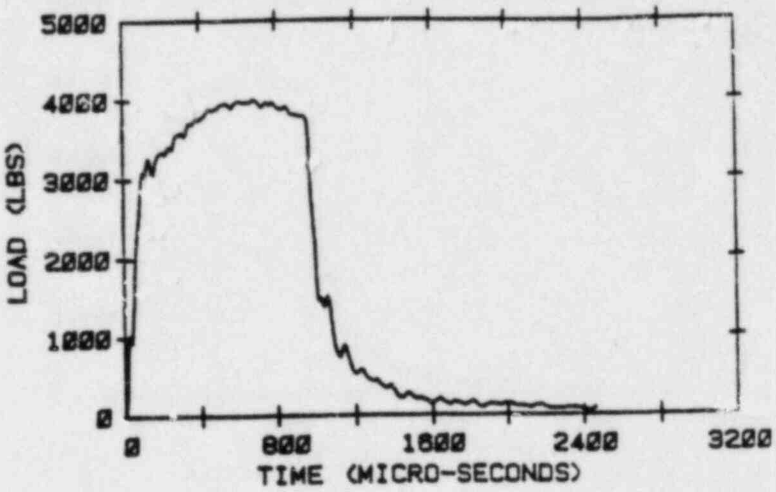
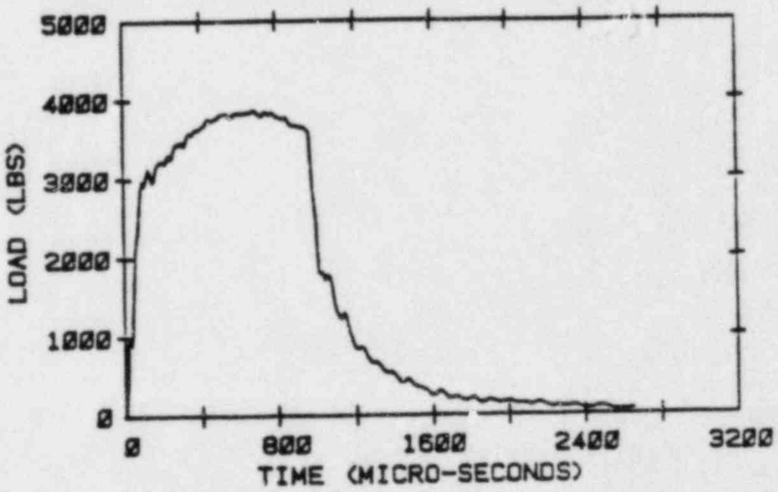


FIGURE A-5. (Continued)

SPECIMEN NO. : JJ7
TEST TEMPERATURE (F) : 19
DIAL ENERGY, (FT-LBS) : 67
GENERAL YIELD LOAD (LB) : 3090
MAXIMUM LOAD (LB) : 4006
FAST FRACTURE LOAD (LB) : 3740
ARREST LOAD (LB) : 1458



SPECIMEN NO. : JJB
TEST TEMPERATURE (F) : 40
DIAL ENERGY, (FT-LBS) : 68.5
GENERAL YIELD LOAD (LB) : 2956
MAXIMUM LOAD (LB) : 3862
FAST FRACTURE LOAD (LB) : 3586
ARREST LOAD (LB) : 1798



SPECIMEN NO. : JKE
TEST TEMPERATURE (F) : 80
DIAL ENERGY, (FT-LBS) : 98
GENERAL YIELD LOAD (LB) : 2914
MAXIMUM LOAD (LB) : 3924
FAST FRACTURE LOAD (LB) : 3114
ARREST LOAD (LB) : 1992

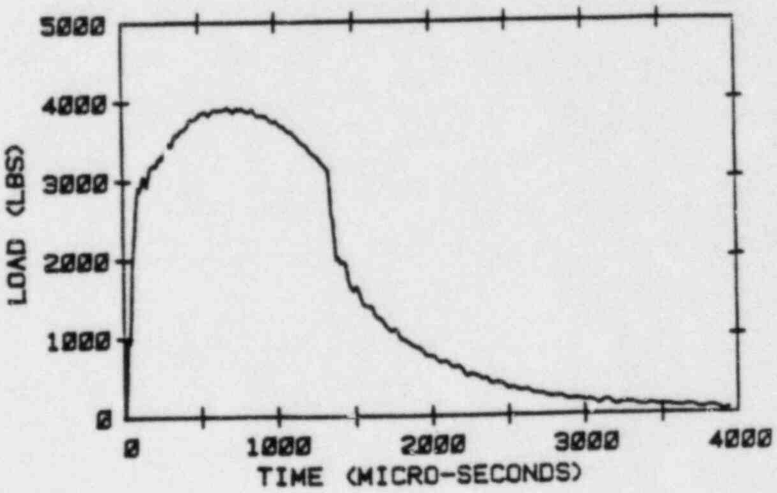
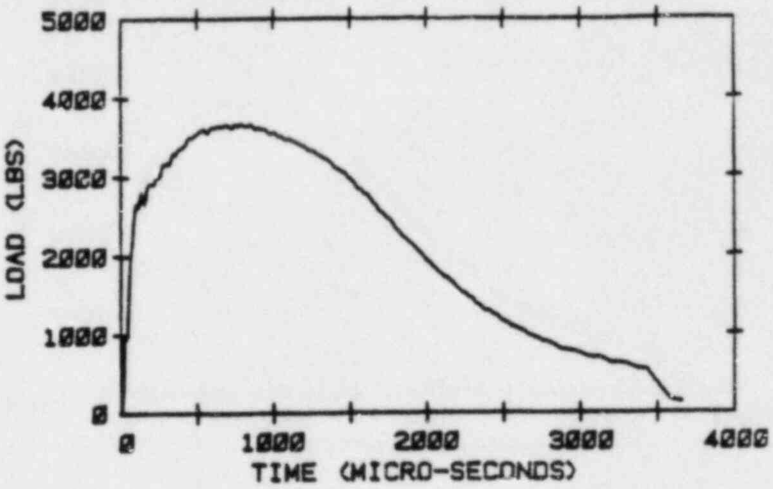
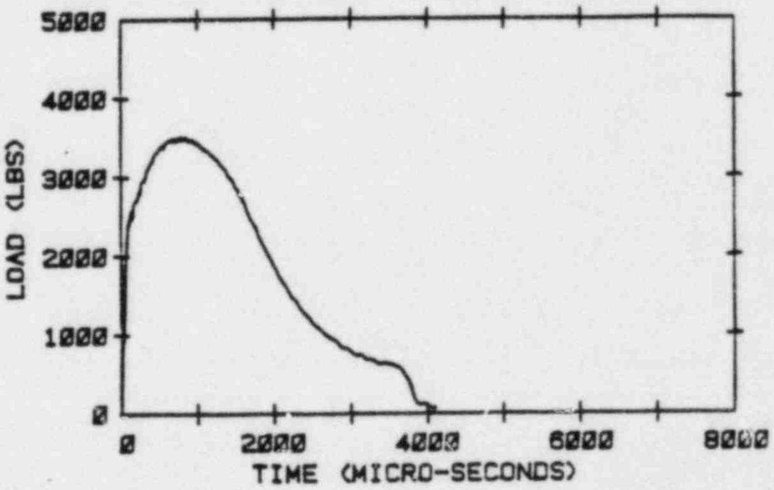


FIGURE A-5. (Continued)

SPECIMEN NO. : JEC
TEST TEMPERATURE (F) : 160
DIAL ENERGY, (FT-LBS) : 120.5
GENERAL YIELD LOAD (LB) : 2852
MAXIMUM LOAD (LB) : 3676
FAST FRACTURE LOAD (LB) : N/A
ARREST LOAD (LB) : N/A



SPECIMEN NO. : JJ3
TEST TEMPERATURE (F) : 240
DIAL ENERGY, (FT-LBS) : 121
GENERAL YIELD LOAD (LB) : 2438
MAXIMUM LOAD (LB) : 3510
FAST FRACTURE LOAD (LB) : N/A
ARREST LOAD (LB) : N/A



SPECIMEN NO. : JJM
TEST TEMPERATURE (F) : 320
DIAL ENERGY, (FT-LBS) : 114.5
GENERAL YIELD LOAD (LB) : 2386
MAXIMUM LOAD (LB) : 3420
FAST FRACTURE LOAD (LB) : N/A
ARREST LOAD (LB) : N/A

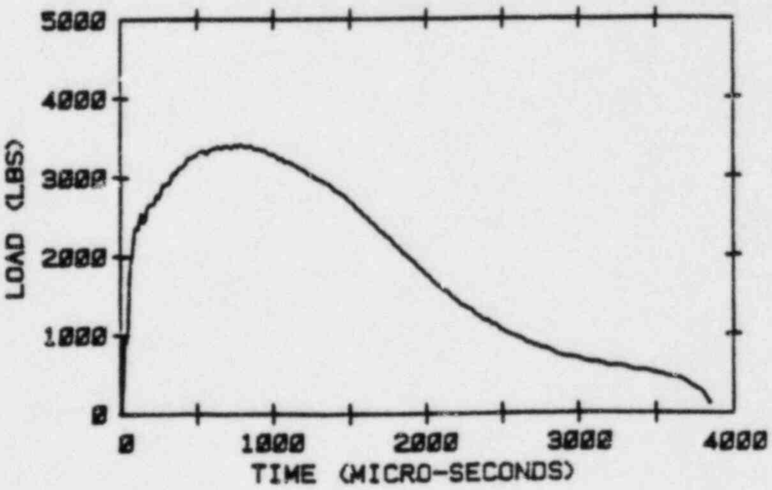
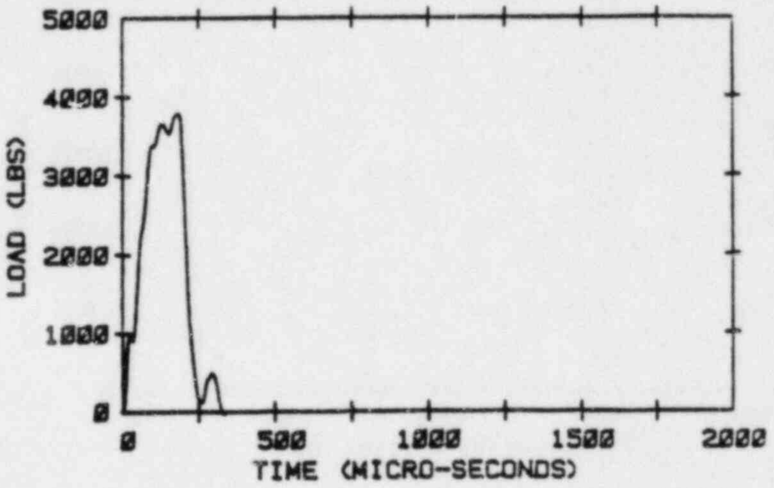
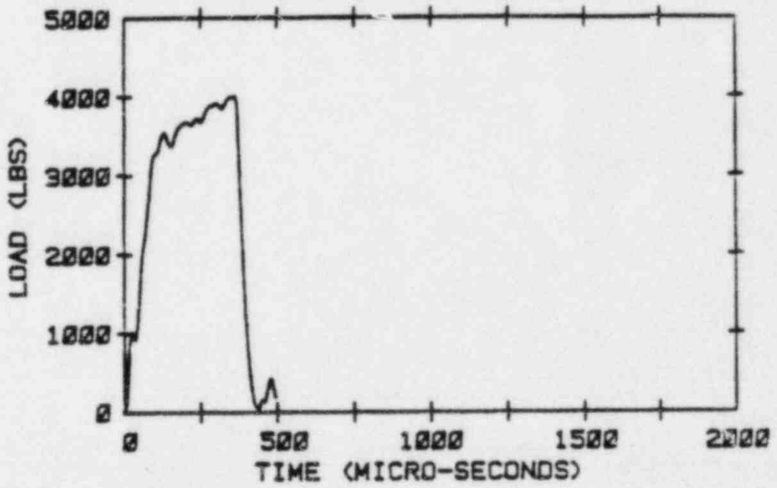


FIGURE A-5. (Concluded)

SPECIMEN NO. : JPA
TEST TEMPERATURE (F) : -80
DIAL ENERGY, (FT-LBS) : 11.5
GENERAL YIELD LOAD (LB) : 3374
MAXIMUM LOAD (LB) : 3788
FAST FRACTURE LOAD (LB) : 3780
ARREST LOAD (LB) : 122



SPECIMEN NO. : JP3
TEST TEMPERATURE (F) : -40
DIAL ENERGY, (FT-LBS) : 23
GENERAL YIELD LOAD (LB) : 3276
MAXIMUM LOAD (LB) : 4006
FAST FRACTURE LOAD (LB) : 3990
ARREST LOAD (LB) : 42



SPECIMEN NO. : JL7
TEST TEMPERATURE (F) : -20
DIAL ENERGY, (FT-LBS) : 63.5
GENERAL YIELD LOAD (LB) : 3174
MAXIMUM LOAD (LB) : 4182
FAST FRACTURE LOAD (LB) : 4082
ARREST LOAD (LB) : 1976

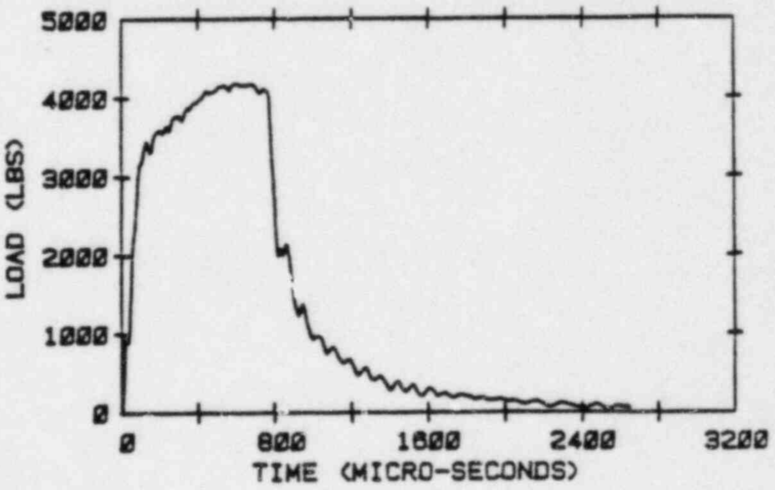
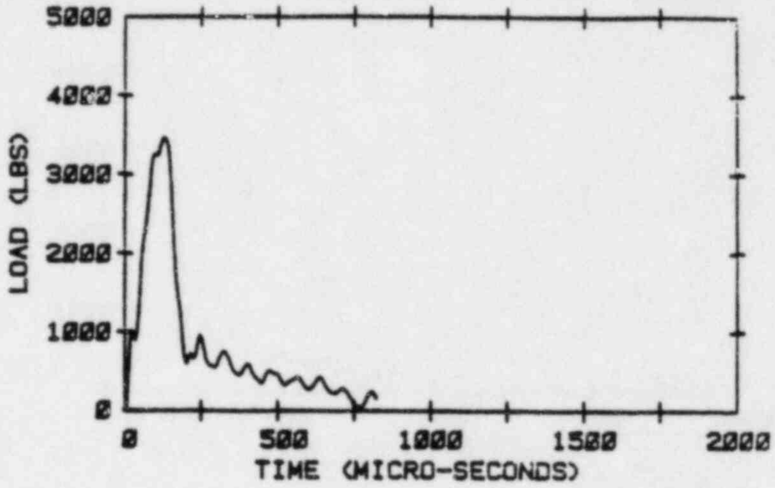
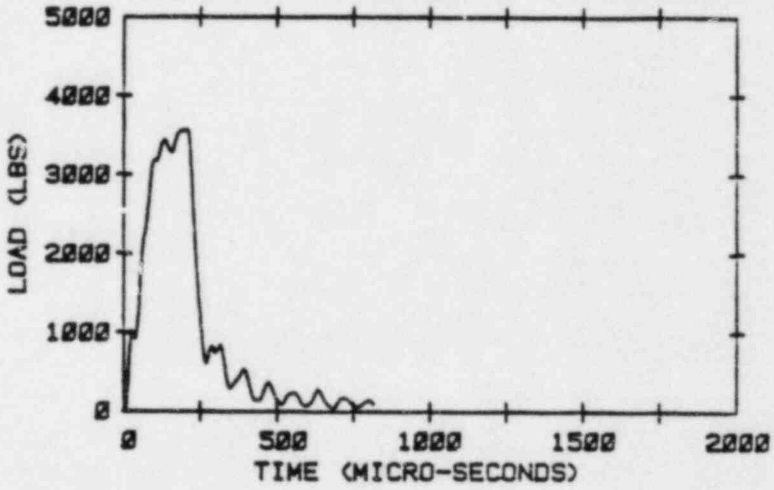


FIGURE A-6. INSTRUMENTED CHARPY IMPACT DATA FOR IRRADIATED HAZ METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

SPECIMEN NO. : JLT
TEST TEMPERATURE (F) : -20
DIAL ENERGY, (FT-LBS) : 12.5
GENERAL YIELD LOAD (LB) : 3254
MAXIMUM LOAD (LB) : 3468
FAST FRACTURE LOAD (LB) : 3454
ARREST LOAD (LB) : 602



SPECIMEN NO. : JP6
TEST TEMPERATURE (F) : 0
DIAL ENERGY, (FT-LBS) : 15
GENERAL YIELD LOAD (LB) : 3184
MAXIMUM LOAD (LB) : 3576
FAST FRACTURE LOAD (LB) : 3564
ARREST LOAD (LB) : 616



SPECIMEN NO. : JP2
TEST TEMPERATURE (F) : 0
DIAL ENERGY, (FT-LBS) : 45.5
GENERAL YIELD LOAD (LB) : 3132
MAXIMUM LOAD (LB) : 4070
FAST FRACTURE LOAD (LB) : 3996
ARREST LOAD (LB) : 1468

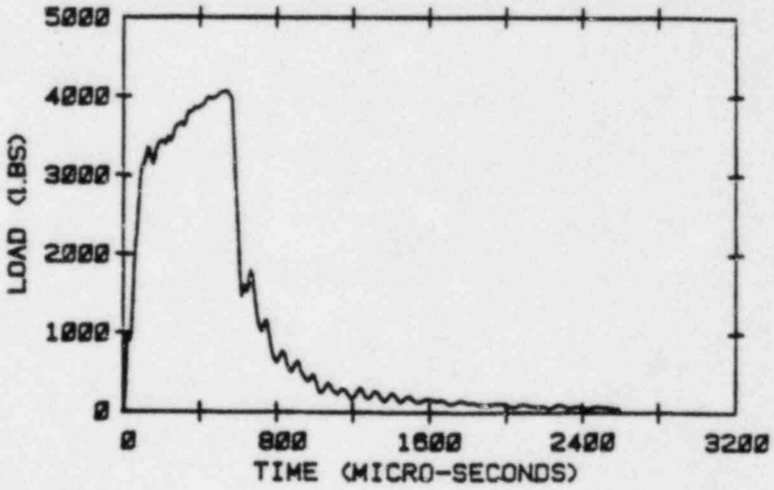
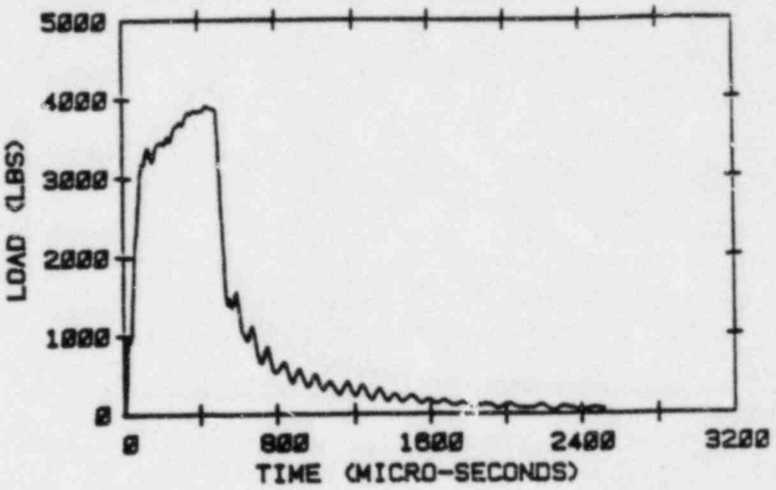
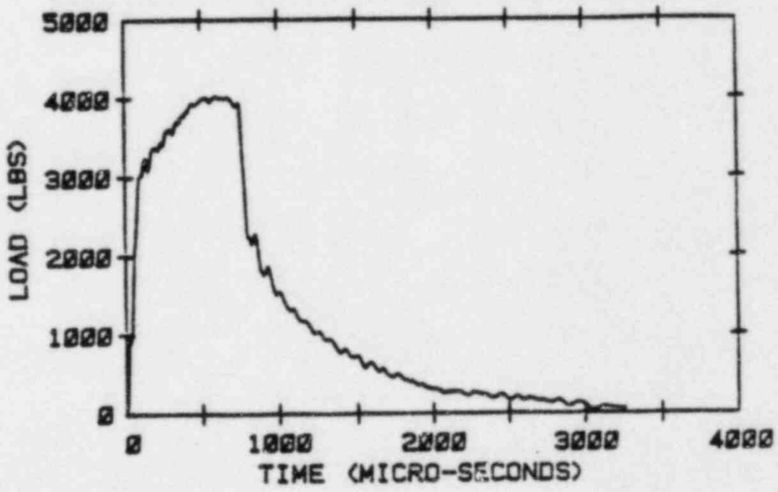


FIGURE A-6. (Continued)

SPECIMEN NO. : LD
TEST TEMPERATURE (F) : 20
DIAL ENERGY, (FT-LBS) : 40.5
GENERAL YIELD LOAD (LB) : 3164
MAXIMUM LOAD (LB) : 3926
FAST FRACTURE LOAD (LB) : 3868
ARREST LOAD (LB) : 1376



SPECIMEN NO. : JP8
TEST TEMPERATURE (F) : 40
DIAL ENERGY, (FT-LBS) : 70.5
GENERAL YIELD LOAD (LB) : 3048
MAXIMUM LOAD (LB) : 4030
FAST FRACTURE LOAD (LB) : 3938
ARREST LOAD (LB) : 2224



SPECIMEN NO. : JP4
TEST TEMPERATURE (F) : 80
DIAL ENERGY, (FT-LBS) : 56.5
GENERAL YIELD LOAD (LB) : 3090
MAXIMUM LOAD (LB) : 3832
FAST FRACTURE LOAD (LB) : 3744
ARREST LOAD (LB) : 2596

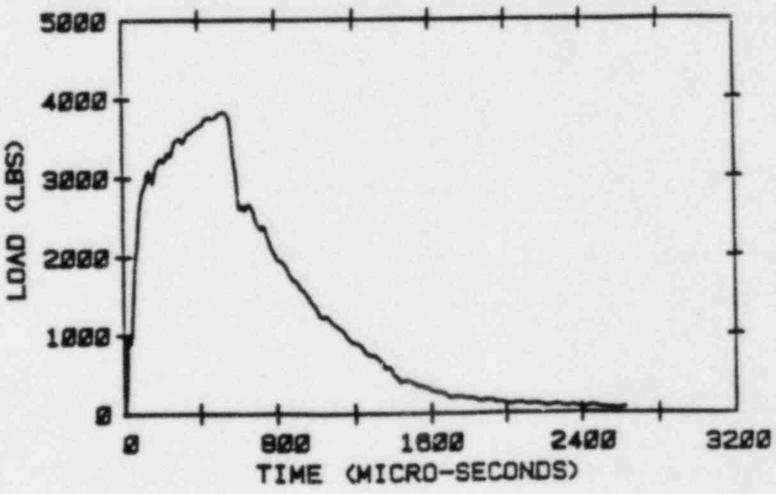
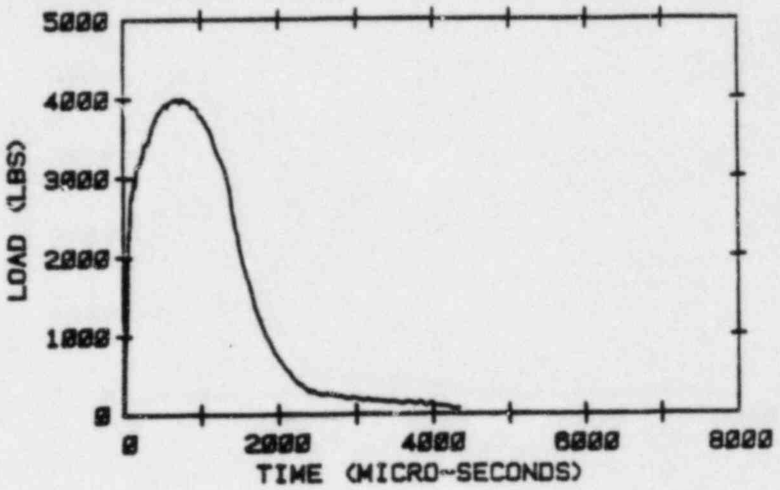
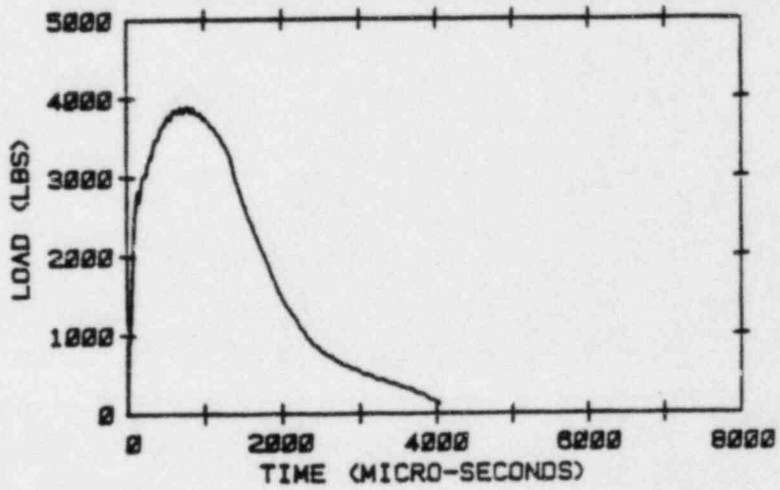


FIGURE A-6. (Continued)

SPECIMEN NO. : JM6
TEST TEMPERATURE (F) : 160
DIAL ENERGY, (FT-LBS) : 105.5
GENERAL YIELD LOAD (LB) : 2804
MAXIMUM LOAD (LB) : 4008
FAST FRACTURE LOAD (LB) : N/A
ARREST LOAD (LB) : N/A



SPECIMEN NO. : JPC
TEST TEMPERATURE (F) : 240
DIAL ENERGY, (FT-LBS) : 116
GENERAL YIELD LOAD (LB) : 2836
MAXIMUM LOAD (LB) : 3900
FAST FRACTURE LOAD (LB) : N/A
ARREST LOAD (LB) : N/A



SPECIMEN NO. : JMD
TEST TEMPERATURE (F) : 320
DIAL ENERGY, (FT-LBS) : 112.5
GENERAL YIELD LOAD (LB) : 2644
MAXIMUM LOAD (LB) : 3622
FAST FRACTURE LOAD (LB) : N/A
ARREST LOAD (LB) : N/A

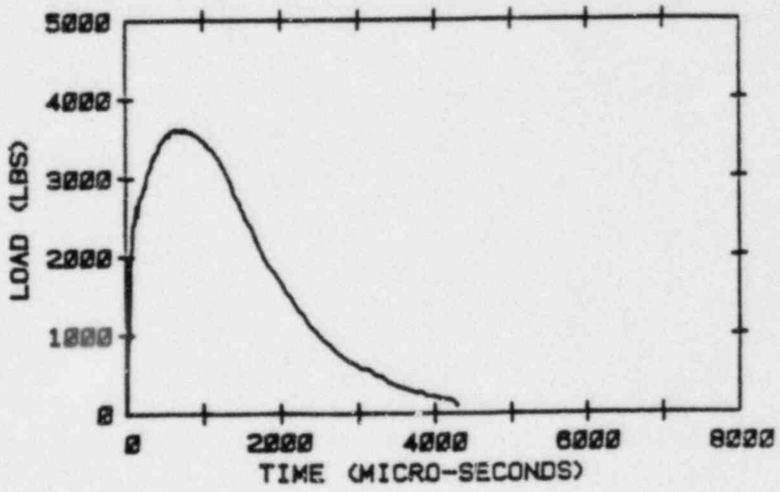


FIGURE A-6. (Concluded)

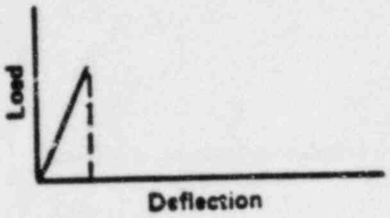
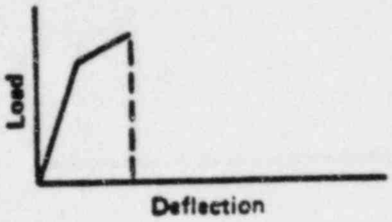
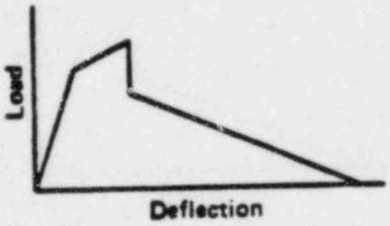
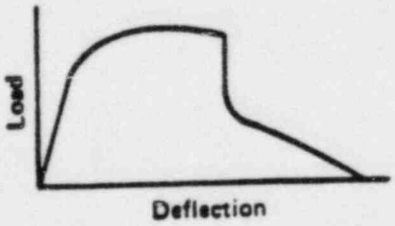
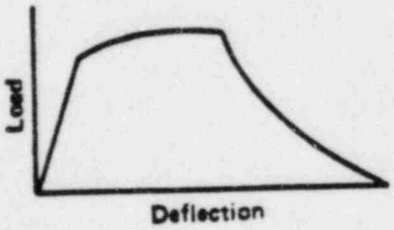
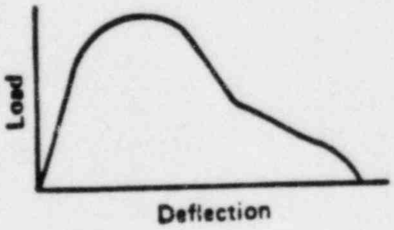
| Fracture Type | Load-Displacement Curves | Raw Data | Remarks |
|---|---|---|---|
| I |  | $P_F$ | Brittle fracture |
| II |  | $P_{GY}$ | Brittle fracture |
| III |  | $P_{GY}$ | Brittle fracture followed by fracture indicative of shear lip formation |
| IV |  | $P_{GY}$,<br>$P_{max}$ | Stable crack propagation followed by unstable brittle fracture and fracture indicative of shear lip formation |
| V |  | $P_{GY}$,<br>$P_{max}$ | Stable crack propagation followed by fracture indicative of shear lip formation |
| VI |  | $P_{GY}$,<br>$P_{max}$ | Stable crack propagation followed by gross deformation |

FIGURE A-8. THE SIX TYPES OF FRACTURES FOR NOTCHED BAR BENDING

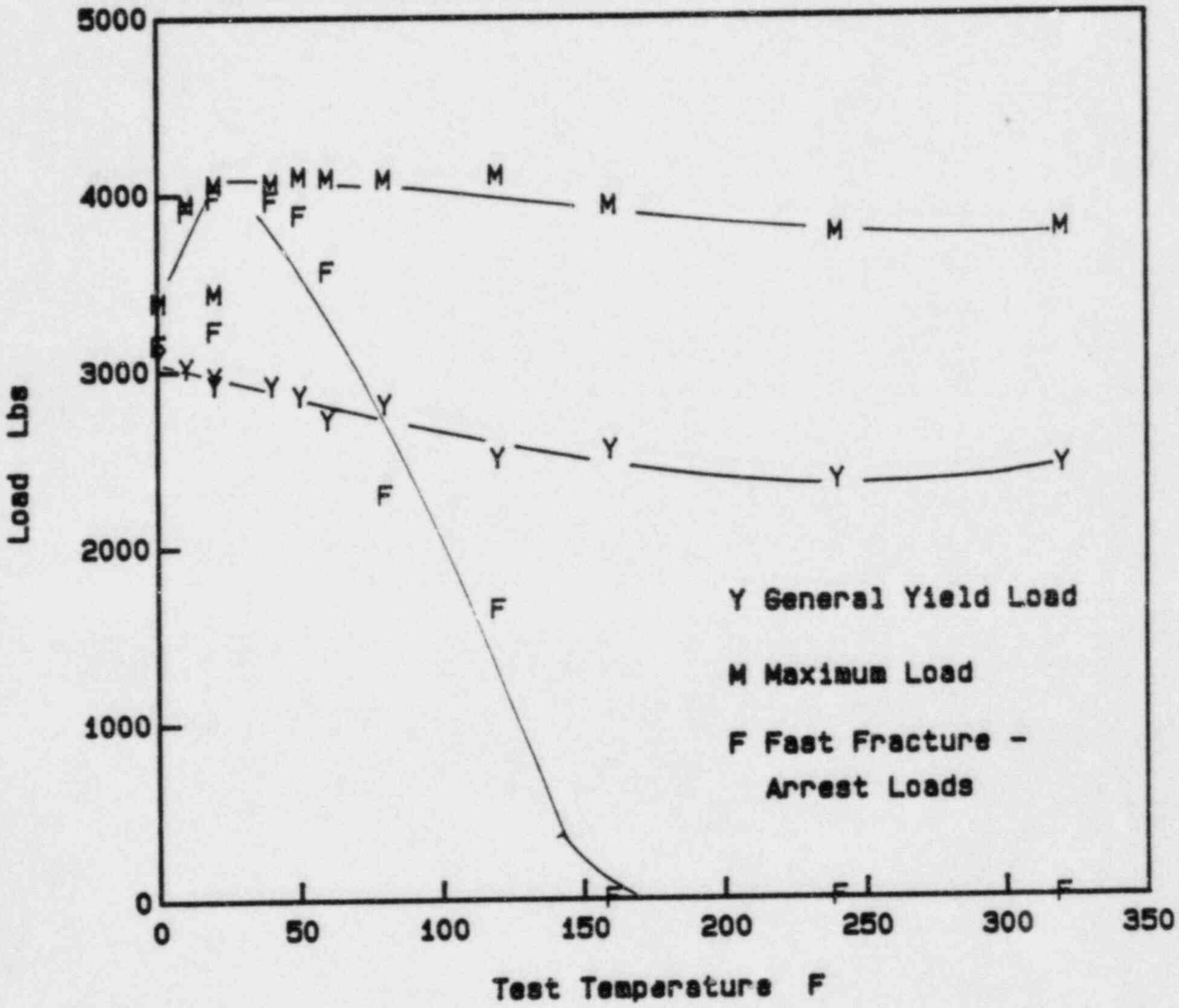


FIGURE A-8. INSTRUMENTED CHARPY LOAD VERSUS TEST TEMPERATURE FOR IRRADIATED BASE METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

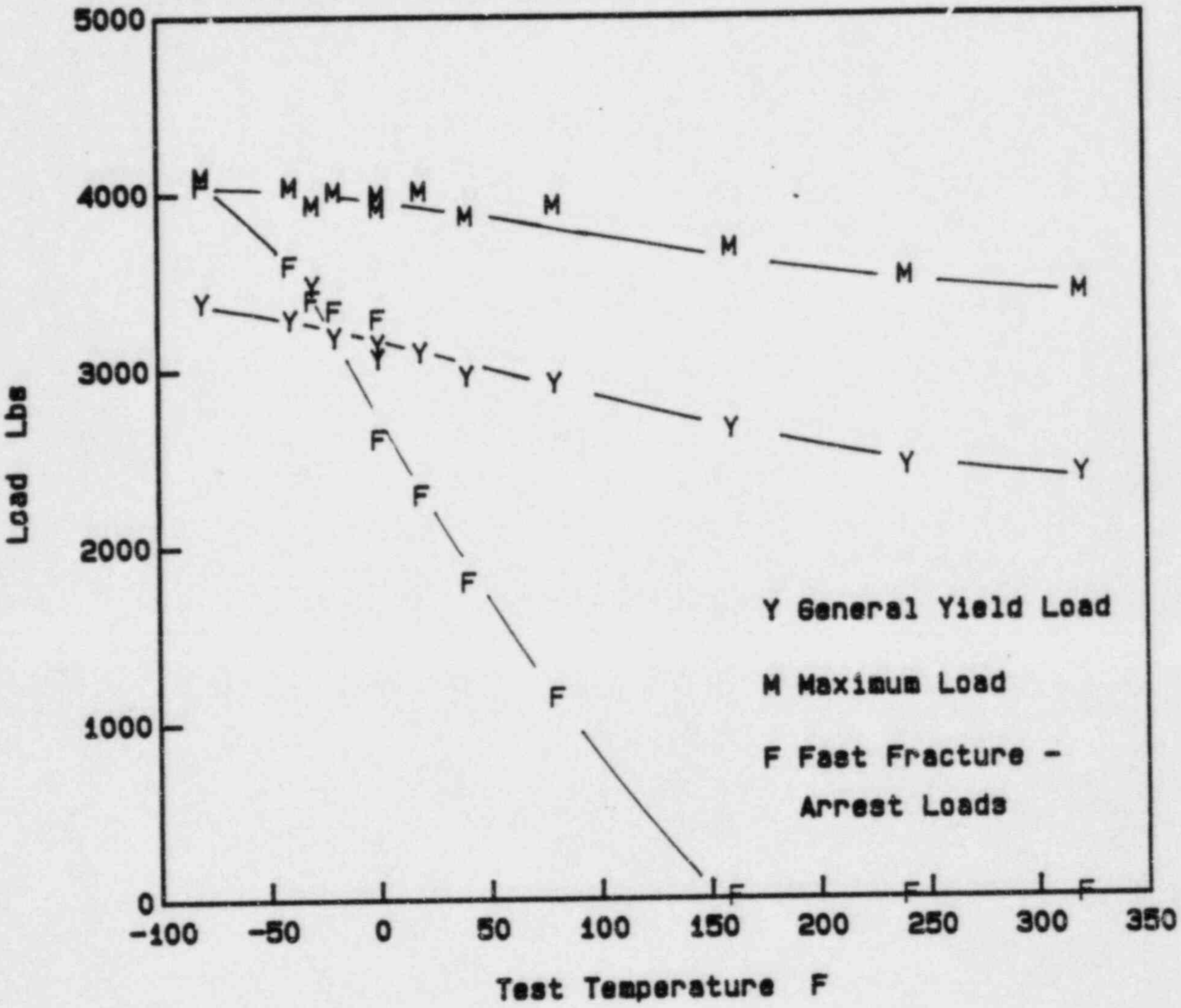


FIGURE A-9. INSTRUMENTED CHARPY LOAD VERSUS TEST TEMPERATURE FOR IRRADIATED WELD METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

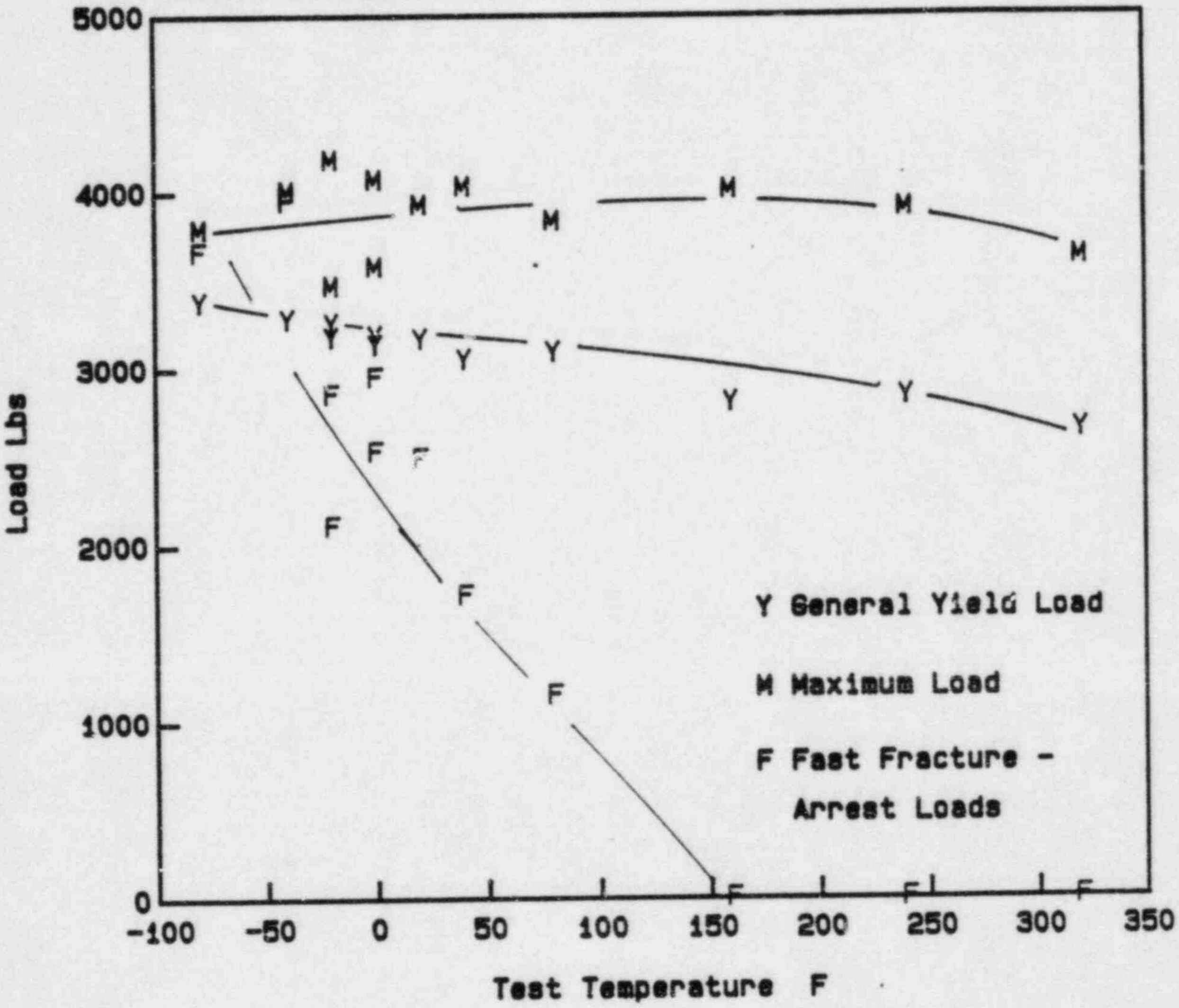


FIGURE A-10. INSTRUMENTED CHARPY LOAD VERSUS TEST TEMPERATURE FOR IRRADIATED HAZ METAL SPECIMENS FROM THE VERMONT YANKEE 30-DEGREE SURVEILLANCE CAPSULE

## APPENDIX A REFERENCES

(1) Wullaert, R. A., "Applications of the Instrumented Charpy Impact Test", in Impact Testing of Metals, American Society for Testing and Materials Special Technical Publication 466, p. 148 (1970).

(2) Perrin, J. S. and Sheckherd, J. W., "Current and Advanced Pressure Vessel Surveillance Specimen Evaluation Techniques", Proceedings of 21st Conference on Remote Systems Technology, American Nuclear Society (1973).

(3) Ireland, D. R., "Procedures and Problems Associated with Reliable Control of the Instrumented Impact Test", in Instrumented Impact Testing, American Society of Testing and Materials Special Technical Publication 563, p. 3 (1973).

(4) Server, W. L., "Impact Three-Point Bend Testing for Notched and Precracked Specimens", Journal of Testing and Evaluation, 6, 1, 29 (1978).

(5) Wullaert, R. A., editor, "C.S.N.I. Specialist Meeting on Instrumented Precracked Charpy Testing", Proceedings, Electric Power Research Institute (1980).

(6) Fearnehough, G. D. and Hoy, C. J., "Mechanism of Deformation and Fracture in the Charpy Test as Revealed by Dynamic Recording of Impact Loads", Iron and Steel Institute, 202, 912 (1964).

(7) Tetelman, A. S. and McEvily, A. J., Fracture of Structural Materials, John Wiley and Sons, Inc., New York (1967).

(8) Kobayashi, T., Takai, K., and Maniwa, H., "Transition Behavior and Evaluation of Fracture Toughness in Charpy Impact Test", Trans. Iron and Steel Institute of Japan, 7, 115 (1967).