Training Manual

APPLIED ENGINEERING PRINCIPLES MANUAL

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Revision: 1, ACN-1

1. **Description of Change:**

   Revision 1 to the AEP included video clips and animations that currently cannot be launched from a .pdf file. In response to a request for quick delivery of a CD ROM containing a .pdf version of the manual, this forwards ACN-1 to the AEP, a limited distribution issue of the AEP that does not include animations or video clips.

   It should be noted that the planned distribution date for a major revision to the AEP is early 2004. This new issue of the AEP will include sophisticated multimedia graphics, video clips, and animations that will illustrate the basic engineering concepts of the manual in a multi-dimensional fashion. The primary delivery medium for the next issue of the manual will be .pdf on CD ROM. Hard copy versions will be available upon request.

2. **Effective Date of Change:** Upon receipt.

   This endorsed form constitutes authority for recipients to use this CD ROM version of the AEP.

3. **Instructions for Entering Change:**

   a. Please use the AEP CD ROM in accordance with local security regulations. If applicable, destroy outdated copies of the AEP in accordance with local procedures.

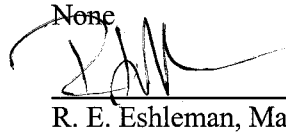
4. **Approval:**

   a. Approval by Naval Reactors: N/A

   b. Approval of other Prime Contractor: Not Required

5. **Cancellation:** None

6. **Authorized Signature:**



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Record of Revisions

Revision 1 (IETM issue only)	June 2001

Record of Advance Change Notices

ACN-1	May 2003

List of Effective Units

Text	Revision in Effect	Revision Date
Title Page	Revision 1, ACN-1	May 2003
i through xiv	Revision 1, ACN-1	May 2003
1-1 through 1-106	Revision 1, ACN-1	May 2003
2-1 through 2-94	Revision 1, ACN-1	May 2003
3-1 through 3-100	Revision 1, ACN-1	May 2003
4-1 through 4-58	Revision 1, ACN-1	May 2003
5-1 through 5-30	Revision 1, ACN-1	May 2003
6-1 through 6-34	Revision 1, ACN-1	May 2003
7-1 through 7-14	Revision 1, ACN-1	May 2003

Chapter 6 — MATERIALS REVIEW

Section 6.1 — Structure Of Metals

6.1.1 — Crystal Structures

Solid materials can be divided into two general classes, **crystalline** and **amorphous**. All metals have a crystalline structure. A crystalline substance is one in which the constituent atoms, ions, or molecules form a repetitive three dimensional array and thus the crystalline substance exhibits long-range order. Salt is an example of a crystalline substance. In contrast, the constituent atoms of an amorphous substance (a substance without definite form) only has short-range order. Glass is an example of an amorphous substance.

The predominant feature of a crystal is the regularity of its structure. This regular arrangement of atoms or molecules is a **crystal lattice**. In a crystal lattice, the smallest group of atoms having all the characteristics of the whole crystal is called the **unit cell**. The simplest unit cell is the cubic, depicted in Exhibit 6-1. Salt crystals have a cubic structure.

Most engineering metals have unit cells that are body-centered cubic (BCC), face-centered cubic (FCC), hexagonal closed-packed (HCP) or body-centered tetragonal (BCT).

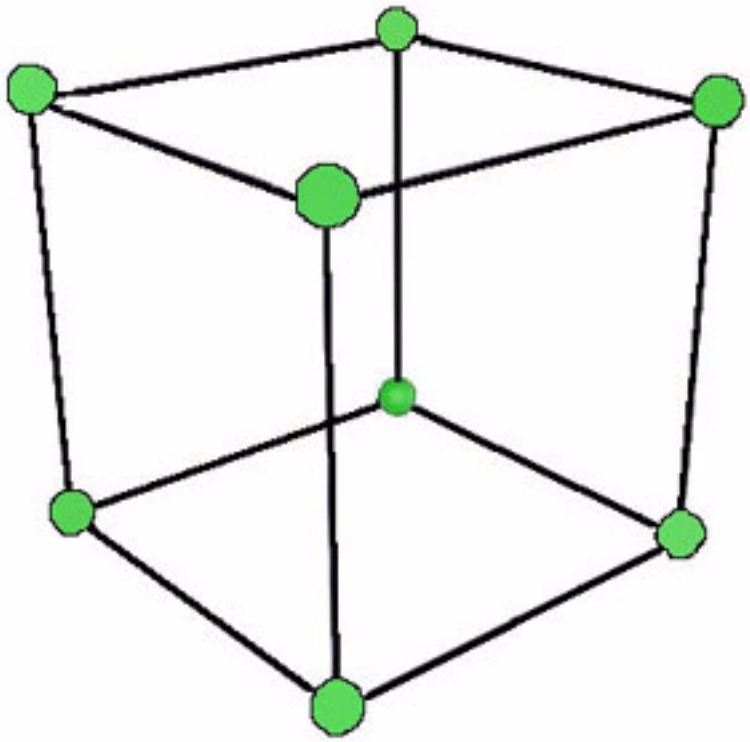

Exhibit 6-1 — Simple Cubic

The **body-centered cubic (BCC)** shown in Exhibit 6-2 consists of eight corner atoms and one atom in the center of the cube. Each corner atom is shared by seven other adjacent unit cells.

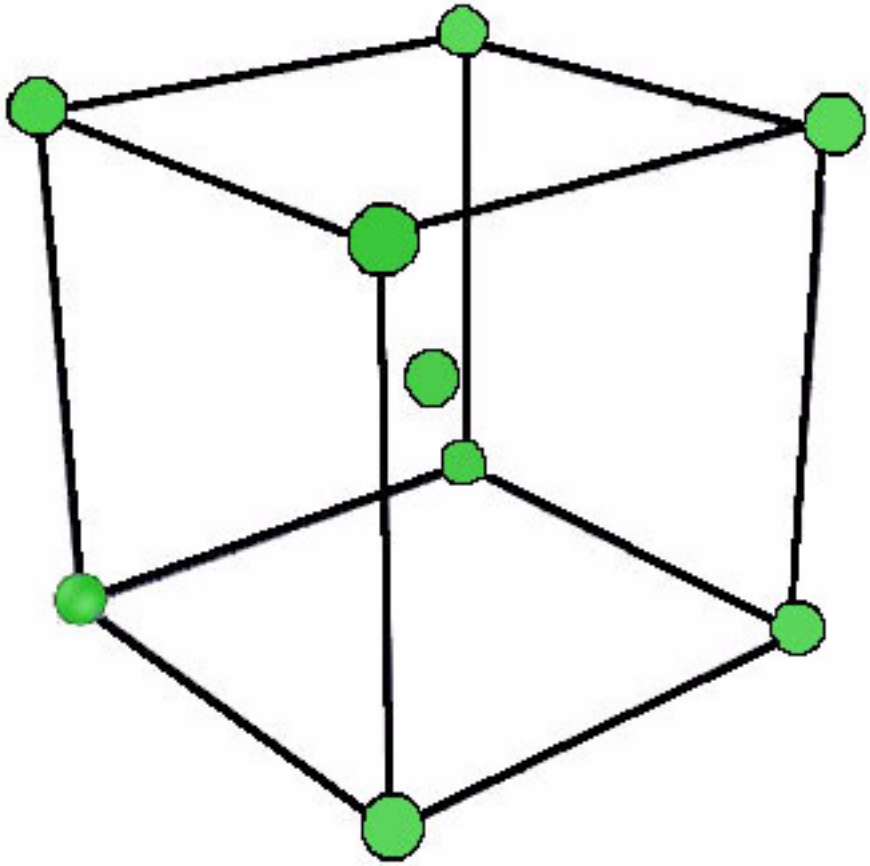

Exhibit 6-2 — Body-Centered Cubic (BCC)

The **face-centered cubic (FCC)** shown in Exhibit 6-3 consists of eight corner atoms and one atom on each of its six faces. Each face atom is equally shared by it's adjacent unit cell face.

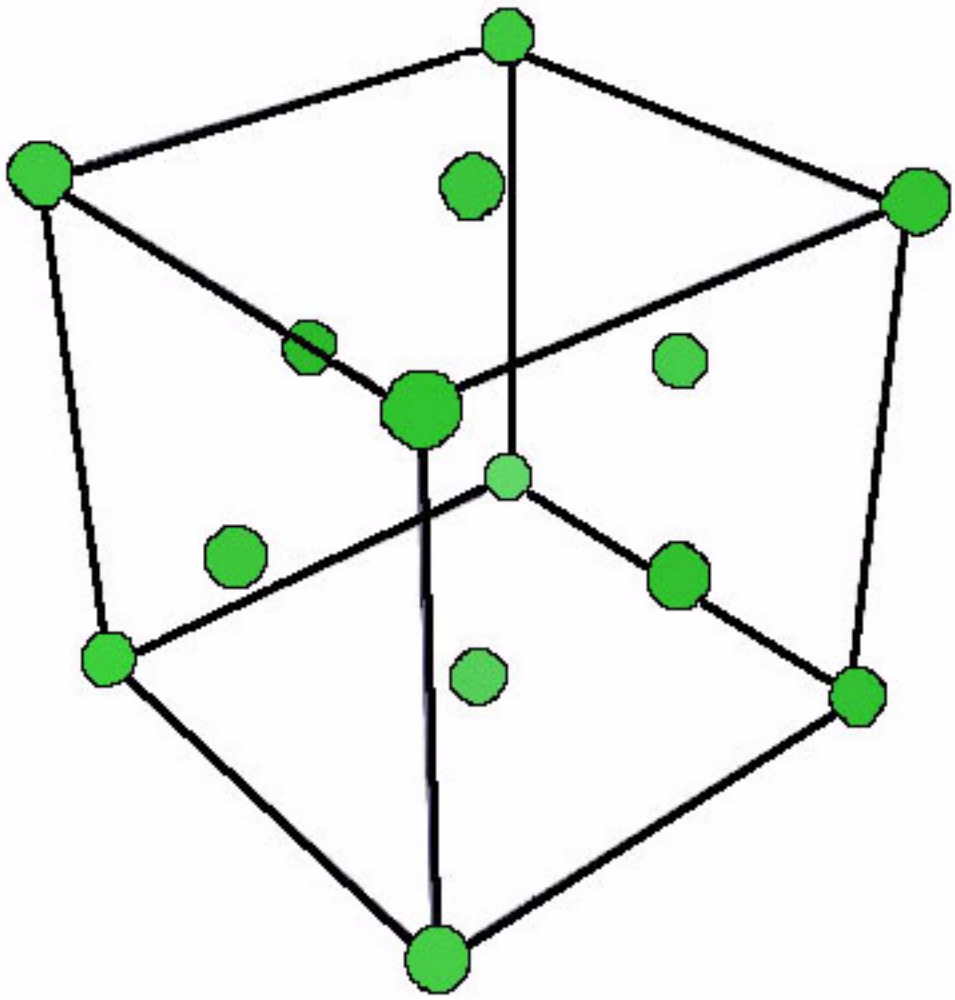

Exhibit 6-3 — Face-Centered Cubic (FCC)

The **hexagonal closed-packed (HCP)** unit cell, shown in Exhibit 6-4, is bound by two hexagons at the bottom and at the top. There is an atom centered on each hexagonal face as well as three atoms forming an equilateral triangle between, and parallel to, the hexagonal faces.

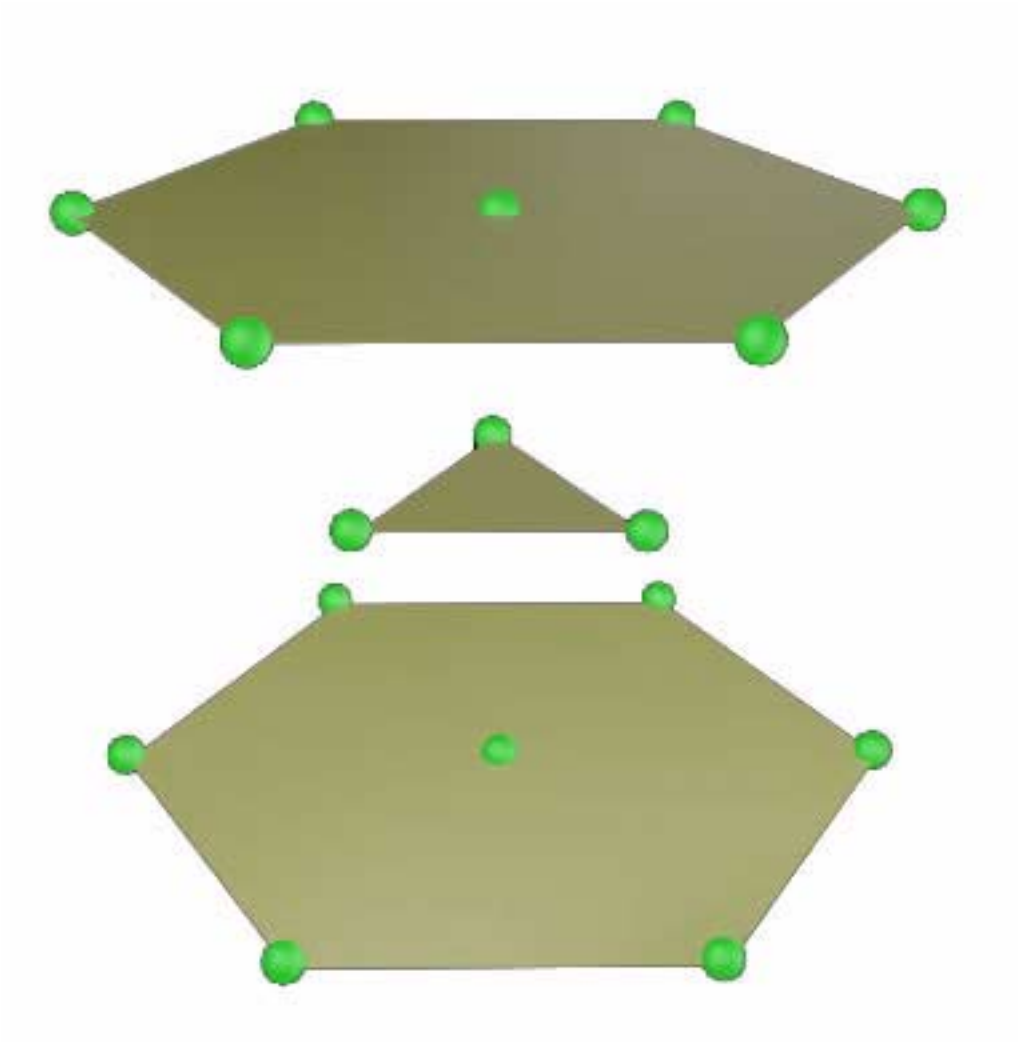

Exhibit 6-4 — Hexagonal Closed-Packed (HCP)

The **body-centered tetragonal (BCT)**, in Exhibit 6-5, is similar to the body centered cubic, but is elongated along one axis.

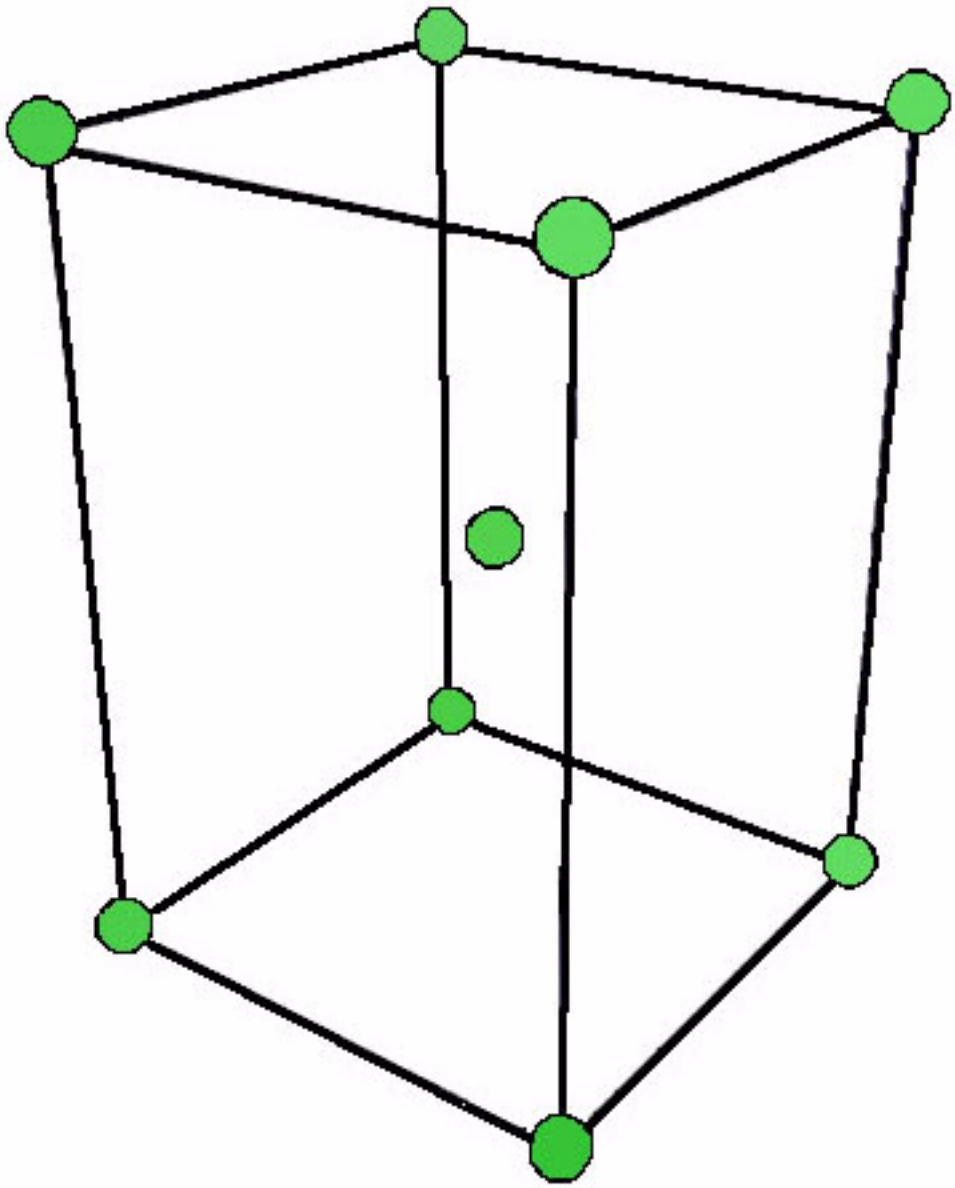

Exhibit 6-5 — Body-Centered Tetragonal (BCT)

6.1.2 — Crystal Imperfections

Real crystals are not perfect. Mechanical strength is profoundly affected by imperfections. If iron could be made free of crystalline imperfections, it could support stresses up to 1.8×10^6 psi in tension. The actual strength of iron is ~10^4psi. Imperfections also have some advantages. For example, in the absence of defects, materials would not exhibit ductility.

Point defects are imperfections involving single atoms. There are three obvious possibilities for defects (depicted in Exhibit 6-6),

- vacancy
- substitutional
- interstitial.

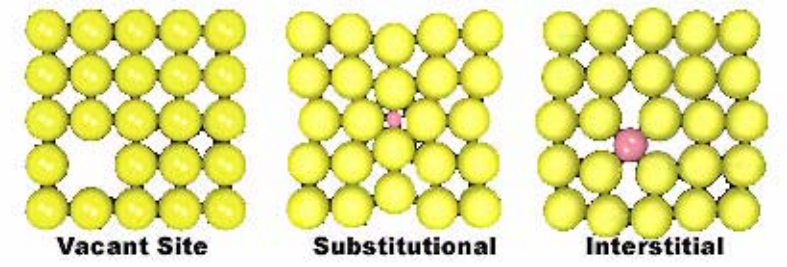

Exhibit 6-6 — Point Defects

For a **vacancy defect**, an atom is simply missing from a lattice position. For **substitutional defects**, a different element's atom is substituted for an original element's atom. For **interstitial defects** an additional atom is in a position that is not a lattice position (between positions). This is an atom at a site that is not occupied in a perfect crystal.

Point defects in crystals occur during solidification in the formation of crystals, by thermal agitation, by cold working, and by exposure to high energy neutrons. **Line defects** are formed by a partial plane of atoms. At the edge of this partial plane of atoms there is a line defect which is called an **edge dislocation**. The atomic arrangement results in a compressive stress along the sides of the extra plane of atoms and tensile stress below the extra plane of atoms. In metals many dislocation lines are curved.

A dislocation is mobile and moves in a direction perpendicular to its length under an applied force. As this process occurs, blocks of metal **slip** past one another and the metal deforms plastically, as depicted in Exhibit 6-7. At elevated temperatures edge dislocations may also move vertically by a process known as **climb**. Such movement is controlled by the rate of movement of atoms and vacancies and can result in the slow deformation (creep) of a metal under very low stresses.

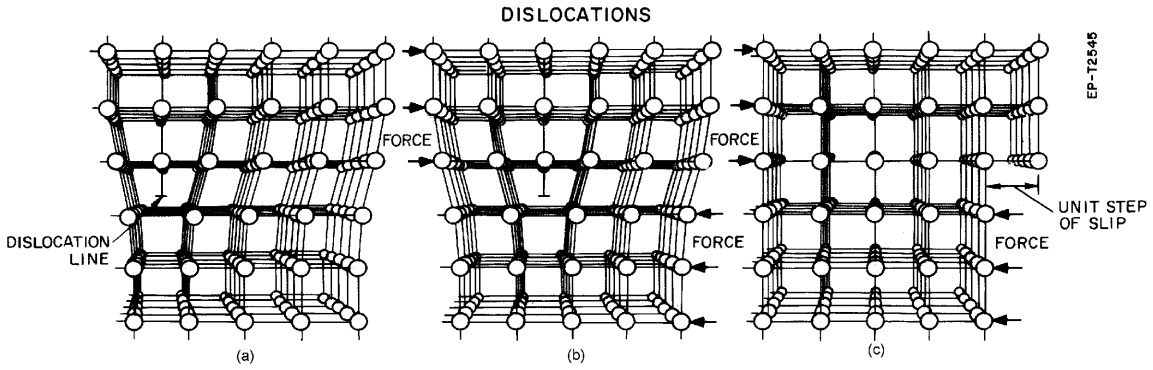

Exhibit 6-7 — Movement Of A Single Edge Dislocation Through A Crystal Resulting In Plastic Deformation

The dislocation is the most important of all the lattice defects. Billions of these imperfections arise during solidification of each cubic inch of metal, and they are intimately connected with nearly all mechanical deformation phenomena. Most methods of strengthening metals produce this effect by **pinning** edge dislocations and impeding slip.

6.1.3 — Grain Boundaries

When a molten metal solidifies, thousands of microscopic, randomly oriented crystals are formed. These crystals are seldom aligned relative to each other. Therefore, local regions of mismatch develop as adjacent crystals grow together. These regions of mismatch, where the crystalline structure is distorted, form the surfaces (**grain boundaries**) of separate crystals or grains.

The internal surfaces formed by grain boundaries strongly influence many material properties. Grain boundaries act as barriers to dislocation movement and therefore affect a metal's strength. A metal with fine grains has more resistance to deformation and thus is stronger than the same metal with large grains.

Grain boundaries are high energy disordered regions which, compared to regions within grains, contain more defects. Hence, polycrystalline metals are stronger than their single crystal counterparts. Impurity atoms, which tend to segregate at grain boundaries, can embrittle a metal and enhance its failure by intergranular corrosive attack. Diffusion is more rapid along grain boundaries especially for small interstitial atoms, such as hydrogen, which embrittles metals.

At elevated temperatures phase transformations nucleate at grain boundaries. In addition, the phenomena known as **grain growth** occurs because the higher energy grain boundaries move outward and grow at the expense of grains with lower energy grain boundaries. At high temperatures grain boundary segregation of impurities diminishes, reducing the tendency of a metal to embrittlement and corrosive attack at grain boundaries.

Section 6.2 — Mechanical Properties Of Metals

6.2.1 — Methods Of Measurement

Mechanical properties characterize the behavior of materials when they are deformed by the application of force. The fundamental variables used to describe the deformation of materials are stress and strain. **Stress** is the force per unit area. The common units of measure for stress are psi (lbf/in^2) and ksi (10^3 psi). **Strain** is the ratio of the deformation (i.e., change in length) to the overall length and is usually expressed in inches of deformation per inch of overall length (in/in). Strain is dimensionless.

Mechanical properties of materials are measured by a variety of mechanical tests that simulate conditions materials must withstand while in service. The most common of these tests are:

1. Tension Test – This test measures the tensile load-carrying ability and amount of deformation a material can withstand before rupture.
2. Hardness Test – This test measures the ability of a material to resist indentation or penetration.
3. Charpy V-Notch Test and Fracture Toughness Test – These tests measure the ability of a material to resist fracturing in the presence of a notch or crack.
4. Creep Test – This test measures the amount of continuous plastic deformation of a tensile specimen over a period of time.
5. Fatigue Test – This test measures the ability of a material to resist breaking when subjected to a fluctuating or alternating load.

6.2.2 — Tension Test

The tension test is the most widely used and one of the most informative of all mechanical tests. In this test, a circular or rectangular test specimen is subjected to a tensile load applied axially to the specimen's ends. In the usual tension test, a constant strain rate test (elongation), the testing machine pulls the ends of the specimen apart at a constant, slow rate while the elongation and resisting force of the specimen are continuously measured. Tested and untested specimens are shown in Exhibit 6-8. From these measurements, the testing machine plots the load versus the elongation. The resulting curve is readily interpreted in terms of stress and strain. The stress value used, termed the **engineering stress**, is calculated using the original cross-sectional area, even though the actual area continuously decreases throughout the test due to necking. The strain value used, termed the **engineering strain**, is defined as the increase in length divided by the original length.

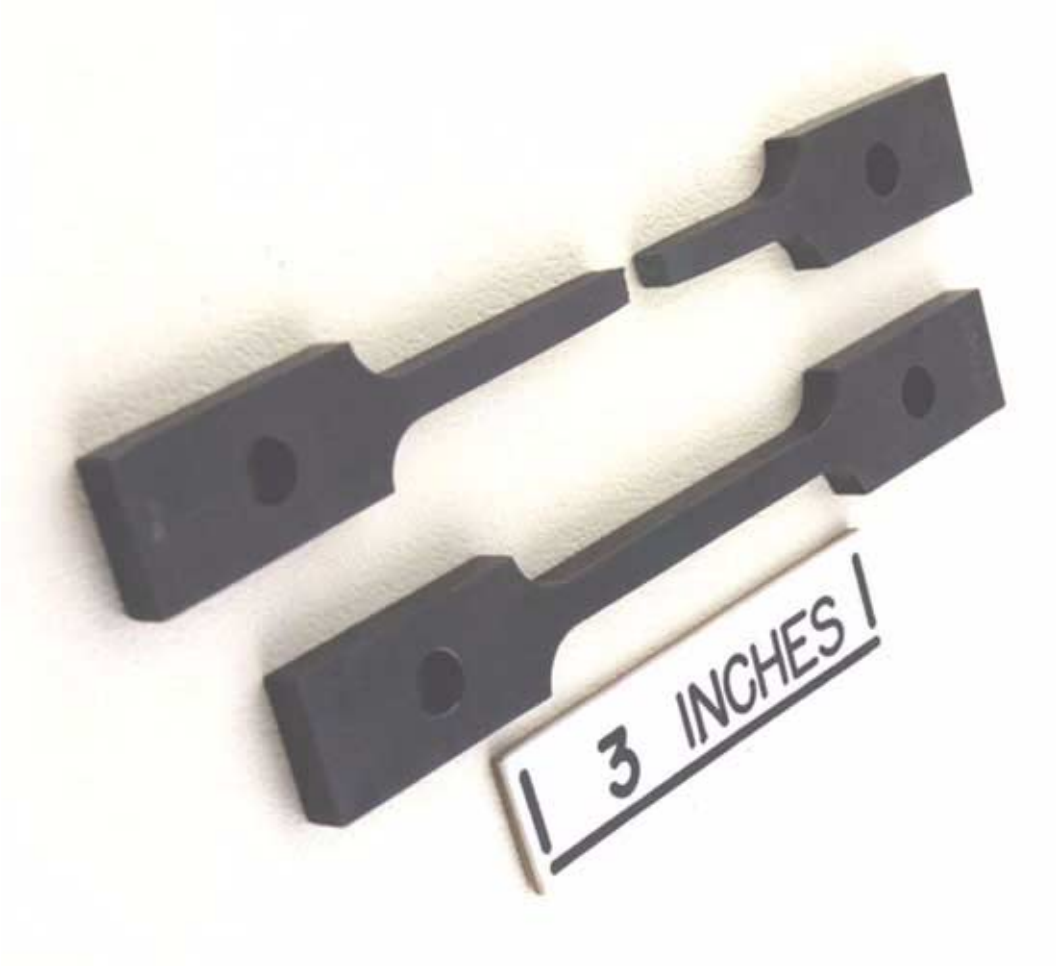

Exhibit 6-8 — Tension Test Specimens

The results of tension tests are **stress-strain curves**. The shape of a stress-strain curve depends on the composition of the material tested, the test temperatures, the strain rate, the heat treatments used to prepare the material, and the test specimen's prior history of plastic deformation, particularly cold working. Exhibit 6-9 illustrates a typical stress-strain curve for a low carbon, low strength structural steel. Because this material exhibits a large amount of straining before the specimen breaks (Point B), it is called a **ductile** material. Another typical stress-strain curve is illustrated in Exhibit 6-10. This material breaks (Point B) after a very small amount of strain and is considered a **brittle** material.

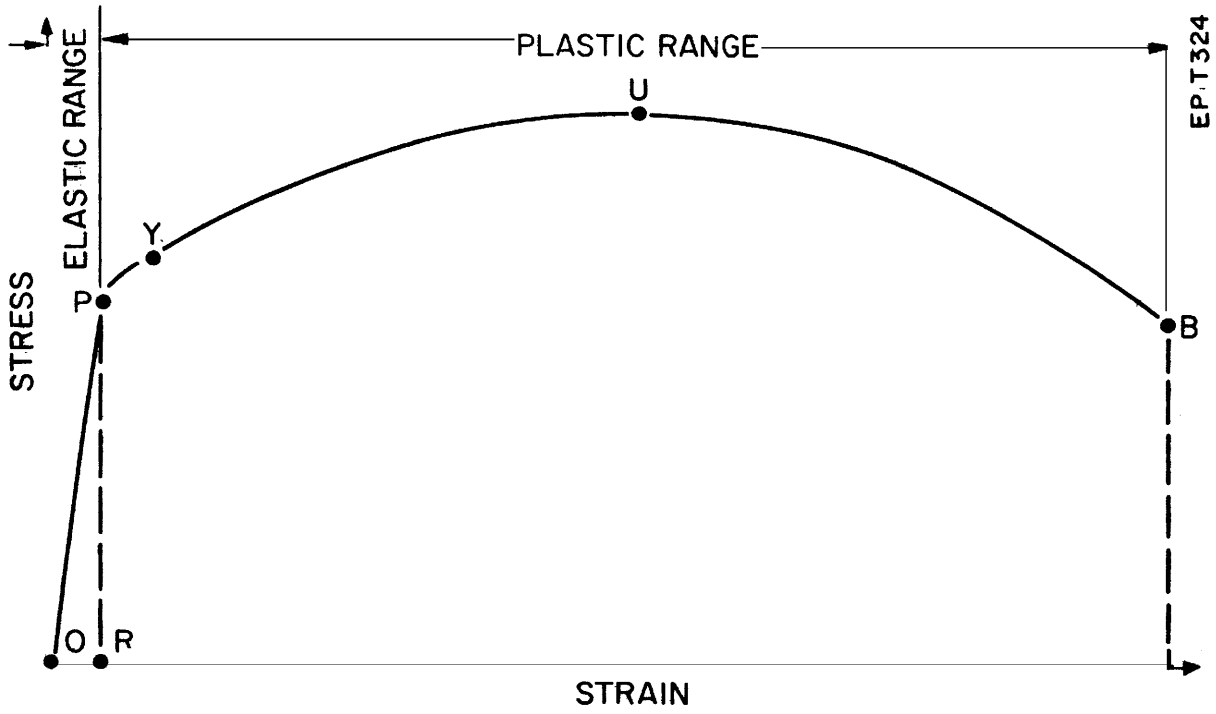

Exhibit 6-9 — Stress-Strain Curve For A Ductile Material

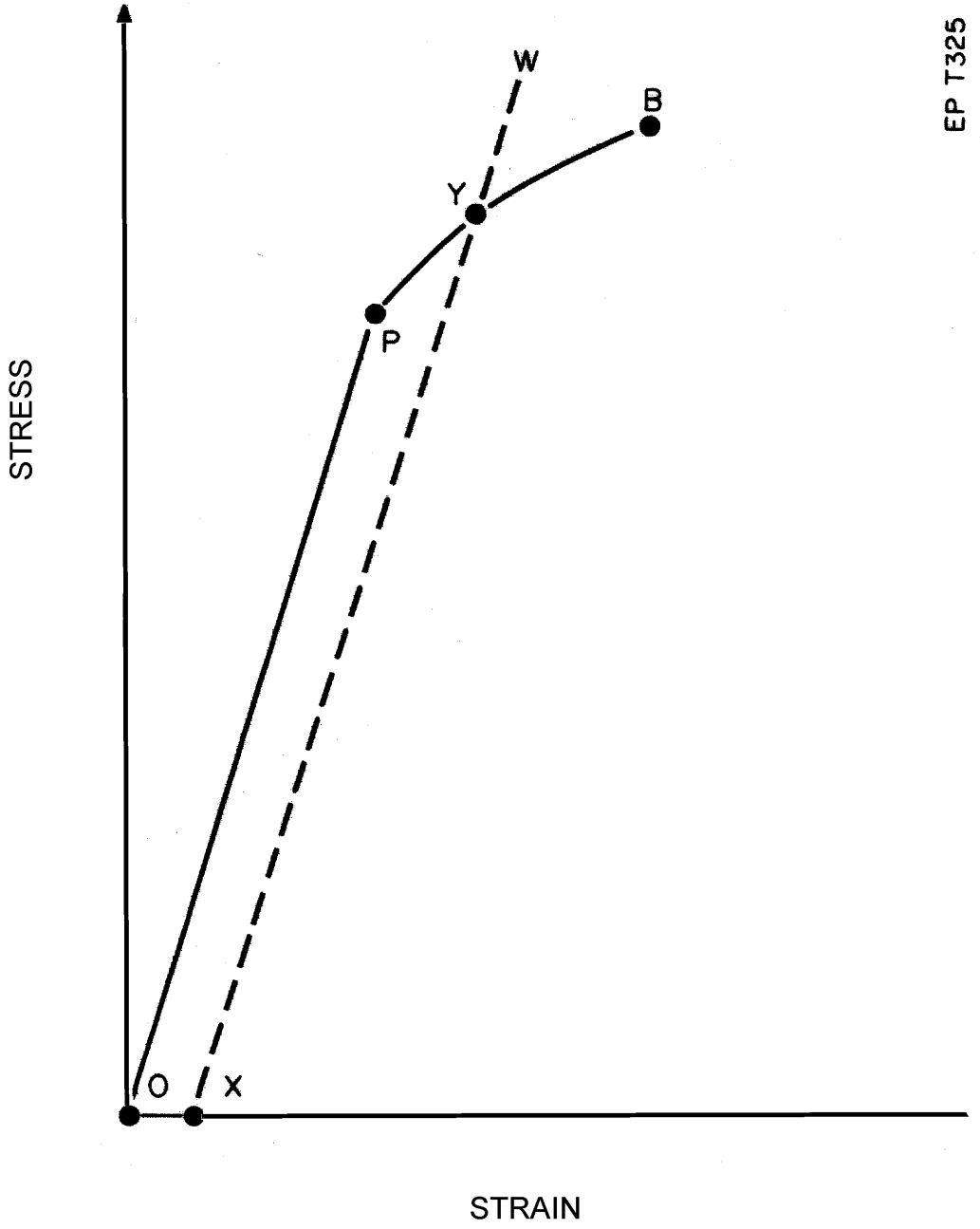

Exhibit 6-10 — Stress-Strain Curve For A Brittle Material

Characteristic points on a stress-strain curve are:

1. Proportional Limit (P) – The highest tensile stress where stress is proportional to strain is the proportional limit.

2. Elastic Limit – The highest tensile stress a specimen can sustain and still return to its original dimensions when the stress is removed. If a stress greater than the elastic limit is applied, permanent plastic deformation occurs within the material, and the specimen does not return to its original size when the stress is removed. Since the elastic limit has a value only slightly higher than the proportional limit for most metals, the plastic limit is approximately represented by Point P. Rubber, however, behaves nonlinearly and has an elastic limit much higher than the proportional limit.
3. Yield Point (Y) – Point on stress-strain curve when plastic straining is easily observed. The usual convention is to define the yield point by the intersection of the deformation curve with a straight line parallel to the proportional/elastic portion and offset a 0.2% on the strain axis.
4. Ultimate Tensile Strength (U) – The maximum stress developed in the material, based upon the original cross-sectional area of the specimen. In a brittle material, the ultimate tensile strength and breaking point will be the same.

The slope of the stress-strain curve up to the proportional limit is a measure of the material's stiffness in the elastic region. This slope is called the **Young's modulus of elasticity (E)**. For example, a tensile stress of 30,000 psi stretches steel about 0.001 inch for each inch of length. Thus, the modulus of elasticity for steel is

$$E = \frac{30,000\,\text{psi}}{0.001\ \text{in/in}} = 30 \times 10^6$$

Nearly all steels have approximately this modulus of elasticity at room temperature. The modulus of elasticity drops to 27×10^6 psi at 400°F.

Ductility is the mechanical property of a material that measures its ability to deform in the plastic range. The two commonly used measurements of ductility are percent elongation and percent reduction of area.

Metals are broadly classified as low strength (25-50 ksi), medium strength (51-100 ksi), and high strength (>100 ksi).

6.2.3 — Hardness

The simplest measure of the mechanical properties of a material is its hardness. In general, high hardness materials have

- more strength
- less ductility
- more susceptibility to brittle fracture.

Exhibit 6-11 illustrates the relationship between hardness (Brinell) and tensile strength for a typical low alloy steel.

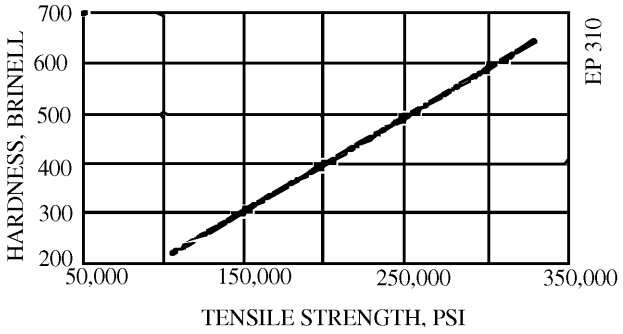

Exhibit 6-11 — Relationship Between Hardness And Tensile Strength For Typical Low-Alloy Steel

The hardness of a material is commonly measured by its ability to resist indentation or penetration. Common hardness tests are:

1. Brinell Test – A hydraulic press forces a small, very hard ball into the test material forming a dent. **The Brinell Hardness Number (BHN)** is the ratio of the applied load to the area of the surface of indentation. The indenter is relatively large (10 mm diameter) compared to the material homogeneities so that the local hardness variations are averaged out. BHNs range from approximately 50 for soft metals to 700 for very hard metals.
2. Rockwell Test – Uses a smaller indenter than the Brinell Test. The Rockwell testing machine applies a load to the indenter and then releases the load, giving a dial reading which is inversely related to the permanent depth of the indentation. This test has a variety of loads and indenters for different ranges of hardness and materials. Results for different loads or indenters are denoted by letters (e.g. Rockwell A, R_A).
3. Knoop Microhardness Test – A pyramid-shaped diamond is pressed into the test material using a small fixed load for a specific time. The hardness is determined by measuring the size of the tiny indentation with a microscope. This test can measure the hardness of very small particles in materials or thin sheets.

6.2.4 — Toughness

Toughness characterizes a material's ability to absorb energy without breaking. It is the opposite of **brittleness**. The manner in which absorbed energy is dissipated is different for breaks in tough and brittle materials. A tough material generally has higher ductility due to dislocation motion along slip planes and the ability of dislocations to overcome barriers by changing their direction of motion along secondary slip planes at an angle to the original slip plane. Dislocation motion requires energy and thus dissipates absorbed energy over a large volume. In a brittle material, a dislocation can move only a very short distance along a primary slip plane before it is stopped; it cannot take off in another direction along a secondary slip plane. As a result, absorbed energy is concentrated at the source and may be sufficient to break interatomic bonds. This will cause the material to **fracture**.

When a metal of high toughness breaks, the broken pieces show considerable deformation. Their irregular and fibrous surfaces result from dislocations slipping in many intersecting planes before a ductile rupture occurs. In contrast, a brittle fracture exhibits little or no plastic straining around the break because dislocation

motion along intersecting planes cannot occur in brittle material. The smooth appearance of the broken surfaces indicates an abrupt transgranular cleavage.

One measure of toughness is the area under the stress-strain curve. This area is the work per unit volume done on the material by the tension test machine. It is the product of strain and stress.

Real structures are not smooth test specimens, but have geometric irregularities or flaws that concentrate stresses and may grow to critical size under load. Most materials fracture below their yield strength when loaded in the presence of a flaw or discontinuity. The resistance of a material to fracture under these conditions is **notch toughness**. Methods that test for notch toughness are:

1. Charpy V-Notch Test - Employs a square bar (55 mm × 10 mm × 10 mm) with a 2 mm deep notch on one side. The test apparatus (see Exhibit 6-13) has a swinging pendulum that is released from a specified height, striking the specimen at the bottom of the pendulum swing. The test specimen is fractured, absorbing energy (slowing down) the pendulum such that it does not swing up as high as it would on a free swing (i.e., no specimen in holder). A calibrated scale on the apparatus converts the height of the pendulum swing to the energy absorbed by the breaking specimen in ft-lbf. Low alloy steels exhibit a **ductile-to-brittle transition** with decreasing temperature (see Exhibit 6-14). It should be noted that tests are usually performed in triplicate because of scatter in the test results. There are several criterion for determining the transition temperature between ductile and brittle cleavage.

Exhibit 6-12 — Charpy Specimens

2. Fracture Toughness Test - A specimen used for this type of test is illustrated in Exhibit 6-15. Specimens range in size from 0.2 inch up to several inches thick, with other dimensions scaled up proportionally. A fatigue crack is grown in each specimen prior to testing by applying a low cyclic load. This simulates the sharp edged cracks encountered in service better than machined

slots or notches. The specimen is loaded, as indicated in Exhibit 6-15, using a tension testing machine as shown in Exhibit 6-16. The fracture toughness (K_{IC}) is determined from the load required to break the specimen and the dimensions of the specimen. Breaking takes place along the plane of the crack. Exhibit 6-17 shows both tested and untested fracture toughness specimens.

3. Drop Weight Test - The drop-weight test is basically a "go, no-go" test which determines the temperature below which a material exhibits essentially no plastic deformation in the presence of a sharp notch and impact loading conditions. This temperature is called the **nil ductility transition temperature (NDTT)**. The specimen is a flat plate with a bead of brittle weld-deposited material at the center. A notch is cut partially through the weld bead as a crack starter. The welded side of the specimen is placed face down on the test fixture, as shown in Exhibit 6-18, and the center of the specimen is struck with a falling weight. The stop in the center of the fixture limits the amount of deflection when the drop-weight strikes the specimen. Under impact, the slight flexure of the specimen opens a crack at the root of the weld notch. The test is repeated at 10°F intervals. If the temperature is low enough, the crack propagates into the specimen material causing it to fracture with virtually no plastic deformation. The NDTT is the maximum temperature at which specimen breakage occurs. The test measures a material's resistance to propagation of a crack leading to brittle fracture.

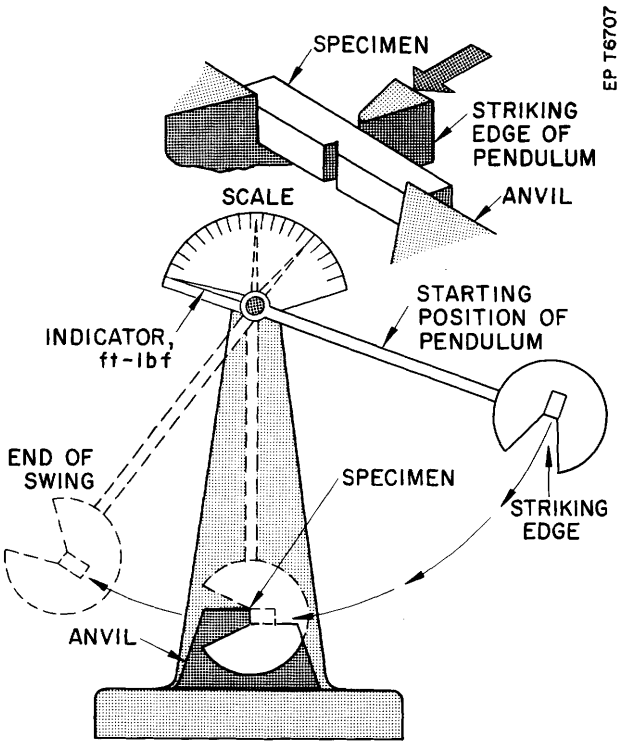

Exhibit 6-13 — Charpy Testing Apparatus (Schematic)

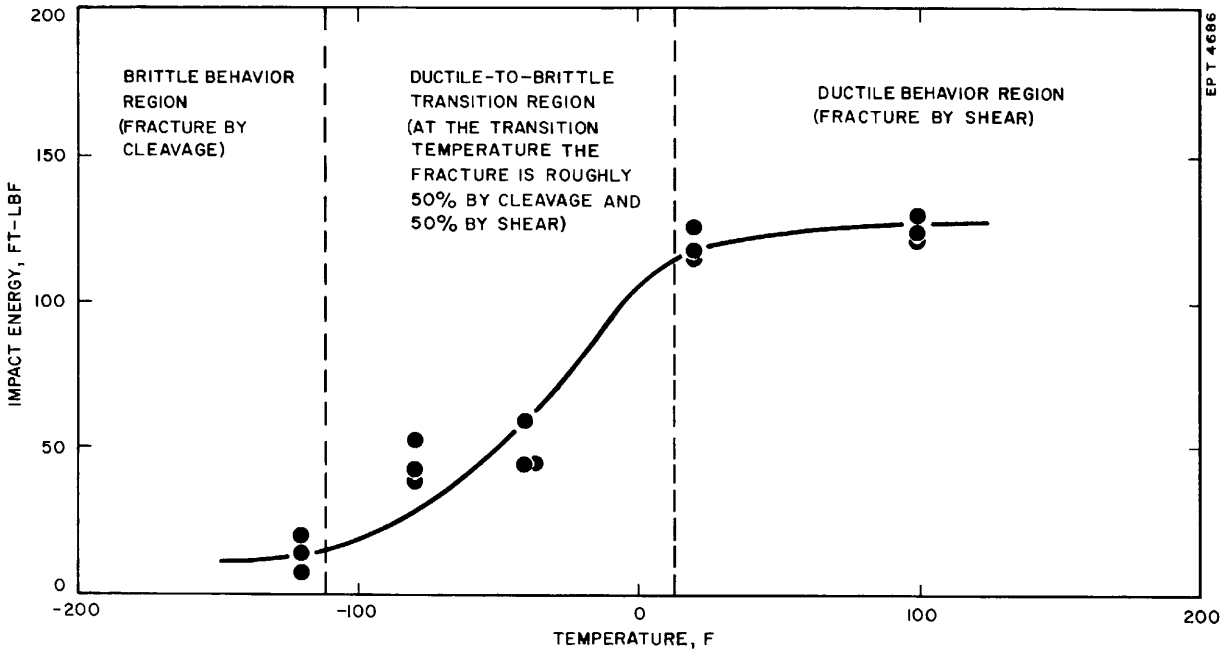

Exhibit 6-14 — Charpy V-Notch Transition Temperature Curve For A Low Alloy Pressure Vessel Steel

Exhibit 6-15 — Test Specimen Used To Measure Fracture Toughness

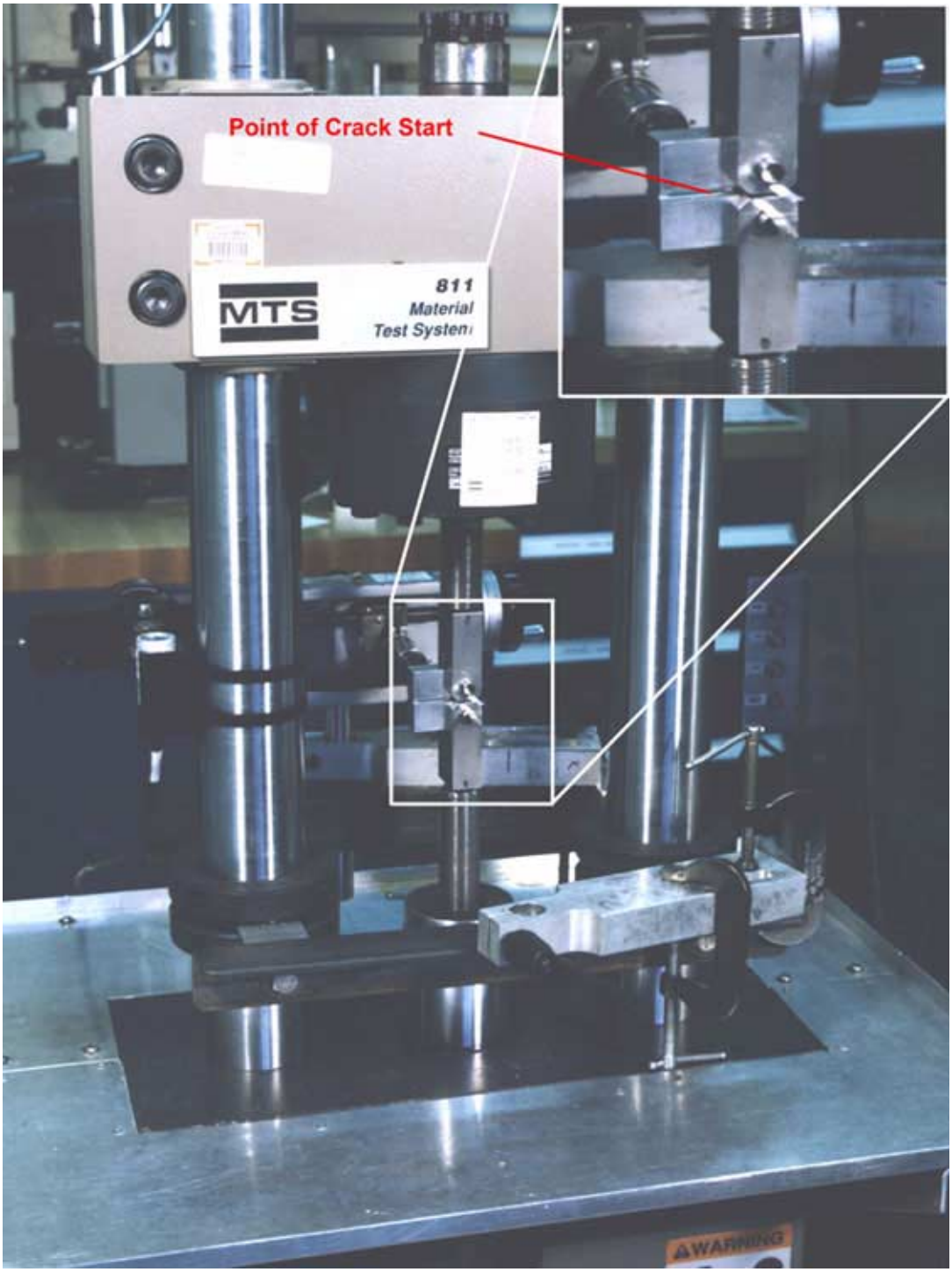

Exhibit 6-16 — Fracture Toughness Test Stand

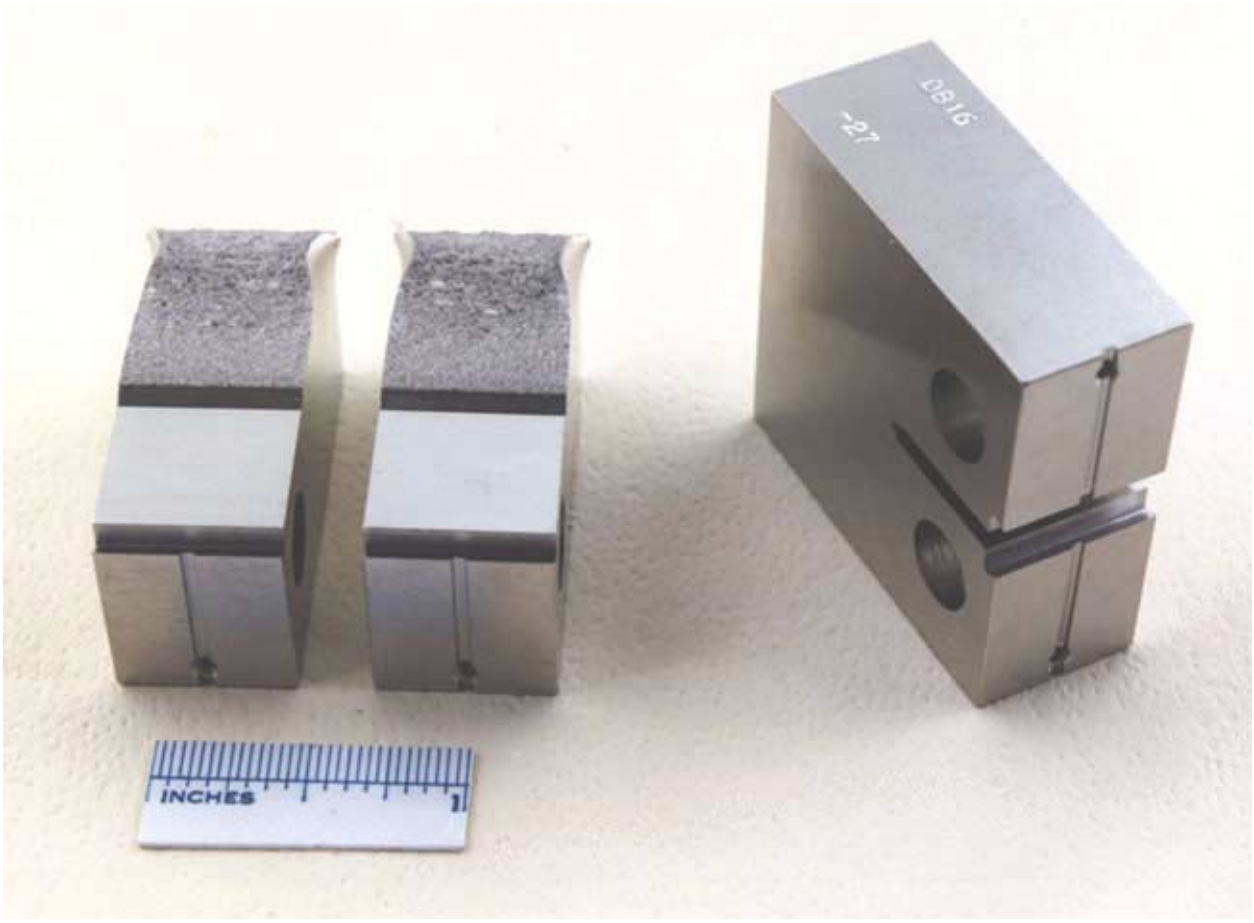

Exhibit 6-17 — Fracture Toughness Specimens

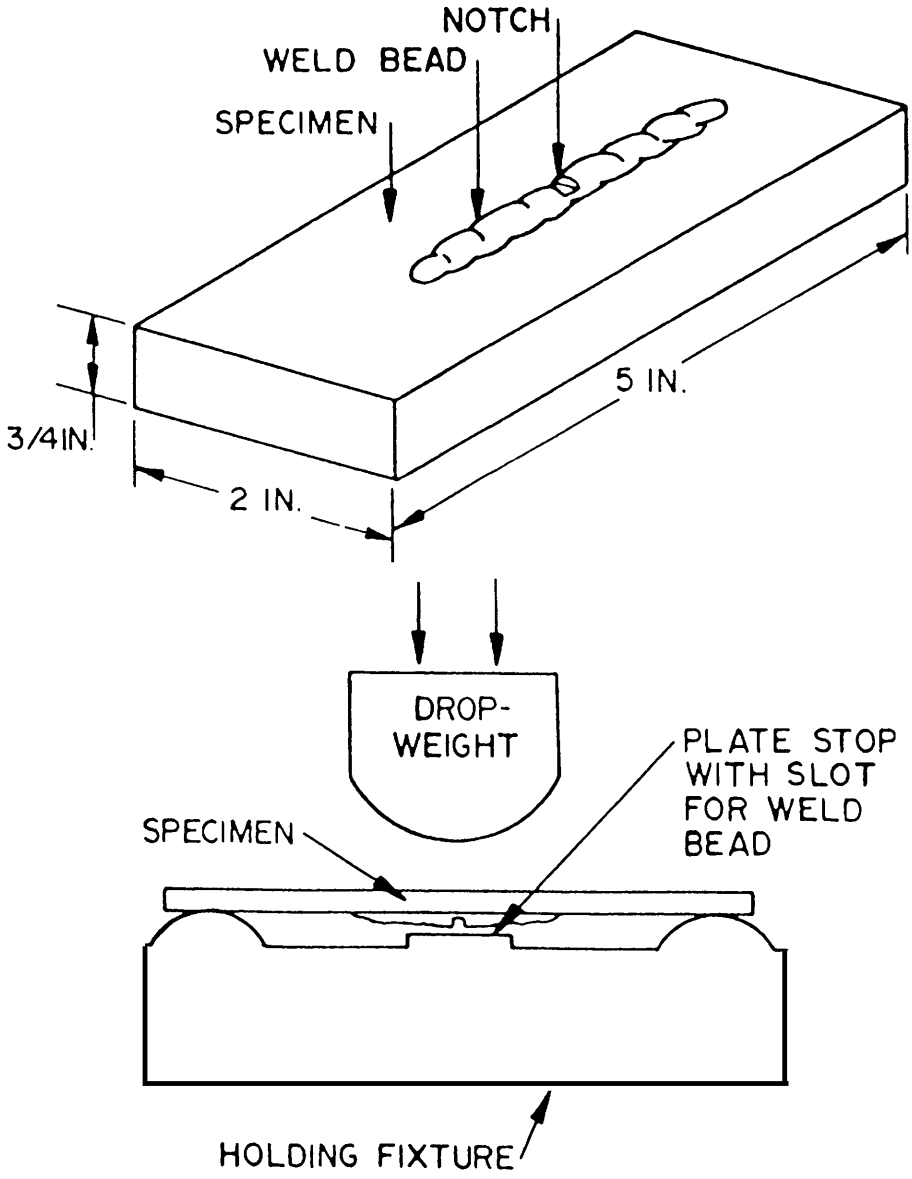

Exhibit 6-18 — Drop-Weight Test

Section 6.3 — Material Failure

6.3.1 — General

Failure is any event which satisfies one of the following conditions: the part becomes completely inoperable; the part remains operable, but it is no longer able to perform its intended function satisfactorily; or the part has suffered serious deterioration that has made it unreliable or unsafe for continued use, thus necessitating its immediate removal from service or replacement. It is good engineering practice to provide a margin between

normal operating loads and those loads expected to cause failure. This type of margin is a **design factor** (sometimes called design margin, safety margin, or factor of safety). The size of the design factor depends on:

- how well actual equipment loadings are known
- what uncertainty exists in our knowledge of material properties
- how precise is our stress analysis
- what manufacturing deviations can exist in the actual component
- what material deterioration can be expected in service
- what experience exists with similar equipment
- how important are cost and weight.

6.3.2 — Ductile Failure

A ductile material will sustain considerable plastic deformation prior to cracking or rupturing. The general characteristics of a ductile rupture are:

- there is extensive distortion which increases progressively as the overload condition is approached, and
- no fragments are formed.

In many structures involving bolted closures, extensive leakage would occur prior to rupture, giving advance warning of ultimate failure. Ductile failure is prevented by assuring that the maximum expected stress is some fraction of the minimum specified yield strength or ultimate strength.

6.3.3 — Brittle Fracture

Pure **brittle fracture** is the type of breaking associated with ceramics or glass. There is essentially no plastic deformation, failure is generally quite sudden, and frequently fragments are formed. Examinations of brittle fractures which have occurred in metal structures have revealed three items that they have in common:

- pre-existing cracks/flaws
- tensile stress
- low fracture toughness.

Brittle fracture of steel occurs at low temperatures. As temperatures are varied it is noticed that there is an abrupt transition between ductile and brittle failure. The temperature of this transition will vary between various alloys and heat treatments.

The most accurate method of determining this transition temperature is with the drop weight test (Paragraph 6.2.4, Item 3). Because of the weld bead preparation and the specimen's larger size, the drop weight test is more cumbersome than the Charpy V-notch test. The Charpy V-notch test is relatively easy to perform, the specimen is conveniently small, and there exists a great amount of data for a wide range of materials. The small size facilitates placing specimens in test reactors to allow estimation of radiation effects.

The correlation between the drop-weight test and the Charpy V-notch test is the **Charpy fix energy (CFE)**. The NDTT is determined by the drop-weight test. Referring to the curve in Exhibit 6-14, an energy level can be determined for a specific temperature. That energy for the NDTT is the CFE. For future correlations, the temperature that matches the CFE is the **nil ductility temperature - Charpy (NDT_{Charpy})**.

A series of specimens of the same alloy is now irradiated (i.e., exposed to neutron flux) to simulate maximum expected service conditions. The Charpy V-notch test results for the irradiated samples provide a curve that

is shifted to the right of the unirradiated sample. By reading the CFE on the irradiated curve, we find a new NDT_{Charpy} for the irradiated material. To account for variations in the data collected, experimental error, and conservatism, 60°F is added to the NDT_{Charpy} to give what is defined as the **reference transition temperature (RTT)**. This is illustrated in Exhibit 6-19. Below RTT the stress on the material must be strictly controlled to prevent brittle fracture.

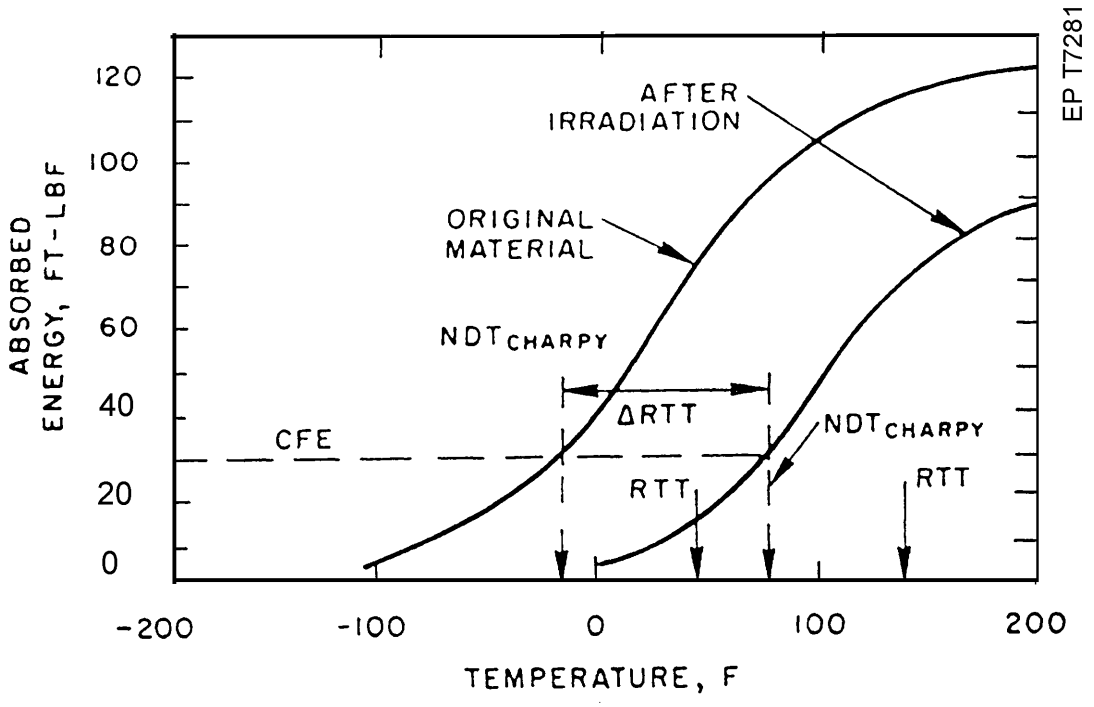

Exhibit 6-19 — Charpy Transition Curves Showing Typical Shift In RTT Due To Radiation Exposure

A fracture mechanics approach is necessary to determine allowable stresses below RTT. **Fracture mechanics** is the study of the behavior of materials containing cracks. At temperatures below RTT, the reduction in load carrying capacity of a structure is closely related to the size of the crack in the structure.

Application of fracture mechanics theory involves establishing design values of the fracture toughness of the material involved, performing detailed stress analyses of the structure, and determining conservative upper bounds for a potential crack's size, shape, and orientation. These values are then used to calculate the maximum plant pressure and heat-up and cooldown rates which can be allowed while preserving an adequate brittle fracture design factor. Finally, allowable pressures and corresponding metal temperatures are related to primary coolant pressures and temperatures which are available to operators through instrumentation.

The **stress intensity factor (K_I)** is a calculated load parameter proportional to the stress magnitude near the tip of a sharp crack in a structural member under tensile load. Mathematically, K_I is defined as

Equation 6-1

$$K_i = C \bullet \sigma_G \bullet \sqrt{a}$$

where:

C = Dimensionless coefficient dependent upon the component and crack geometry and method of loading.

σ_G = Gross Stress (ksi)

a = Crack size or depth (inches).

When the **gross stress (σ_G)** is equal to the **fracture stress (σ_F)**, i.e., the stress at which brittle fracture occurs, then the stress intensity factor (K_I) equals the **critical stress intensity (K_{IC})**. K_{IC} is also known as the fracture toughness. **Fracture toughness** is a material property which is a measure of a material's ability to withstand tensile stress in the presence of a flaw without crack growth by brittle fracture. Mathematically, fracture toughness is defined to be:

Equation 6-2

$$K_{IC} = C \bullet \sigma_F \bullet \sqrt{a}$$

K_{IC} is a measurable value. It is determined using the fracture toughness test (Paragraph 6.2.4). Test results can determine limiting values of K_{IC} over a range of temperatures.

Allowable stress (σ_a) is the maximum value of gross stress (σ_G) which may be permitted without exceeding stress limits (including design factor) imposed by brittle fracture theory. It is defined as

Equation 6-3

$$\sigma_a = \frac{K_{IC}}{DF \bullet C \bullet \sqrt{a}}$$

where:

DF = Minimum Specified Design Factor.

The allowable stress in a design is the sum of **residual**, **thermal**, **reaction** and **pressure** stresses, as shown in Equation 6-4.

Equation 6-4

$$\sigma_{total} = \sigma_P + \sigma_R + \sigma_T + \sigma_{reaction}$$

Residual and reaction stresses are unaffected by operator action. Thermal and pressure stresses can be controlled by the operator. Thermal stresses are limited by fatigue limits for heat-up and cooldown rates.

Pressure stresses are controlled by controlling system pressure. If thermal stresses are controlled within specific limits for heat-up and cooldown rates, then **allowable pressure stress (σ_P)** is the only parameter to be controlled by the operator. By methods beyond the scope of this manual, a **pressure-stress conversion factor (PSCF)** can be determined such that

Equation 6-5

$$\sigma_P = \sigma_{total} - \sigma_R - \sigma_T - \sigma_{reaction}$$

Equation 6-6

$$P_a = \frac{\sigma_P}{PSCF}$$

where:

P_a = allowable system pressure (psi).

With corrections for instrument errors, limits on pressure for specific plant temperatures can now be determined for all plant components susceptible to brittle fracture. The most limiting component limits, combined with additional design factors, are combined to form a series of pressure-temperature limits known as **brittle fracture protection limits (BFPL)**. Refer to Reference 2 for a detailed discussion.

6.3.4 — Creep

Creep, the slow, continuous, permanent (plastic) deformation of a metal under a steady load can occur at stress levels less than the material's yield stress. Creep rate is proportional to load (i.e., creep rate decreases as the load decreases). Creep can be accelerated by fast neutron irradiation. Creep behavior is important to core design, as discussed in Reference 1 .

In a standard creep test, a specimen similar to a tension load specimen is subjected to a constant axial load in an oven that maintains a uniform test temperature. A typical test setup is shown in Exhibit 6-20. The results consist of measurements of specimen elongation with time. From this elongation data, the known tensile load, and specimen dimensions, stress and strain are determined. Exhibit 6-21 shows both tested and untested creep test specimens.

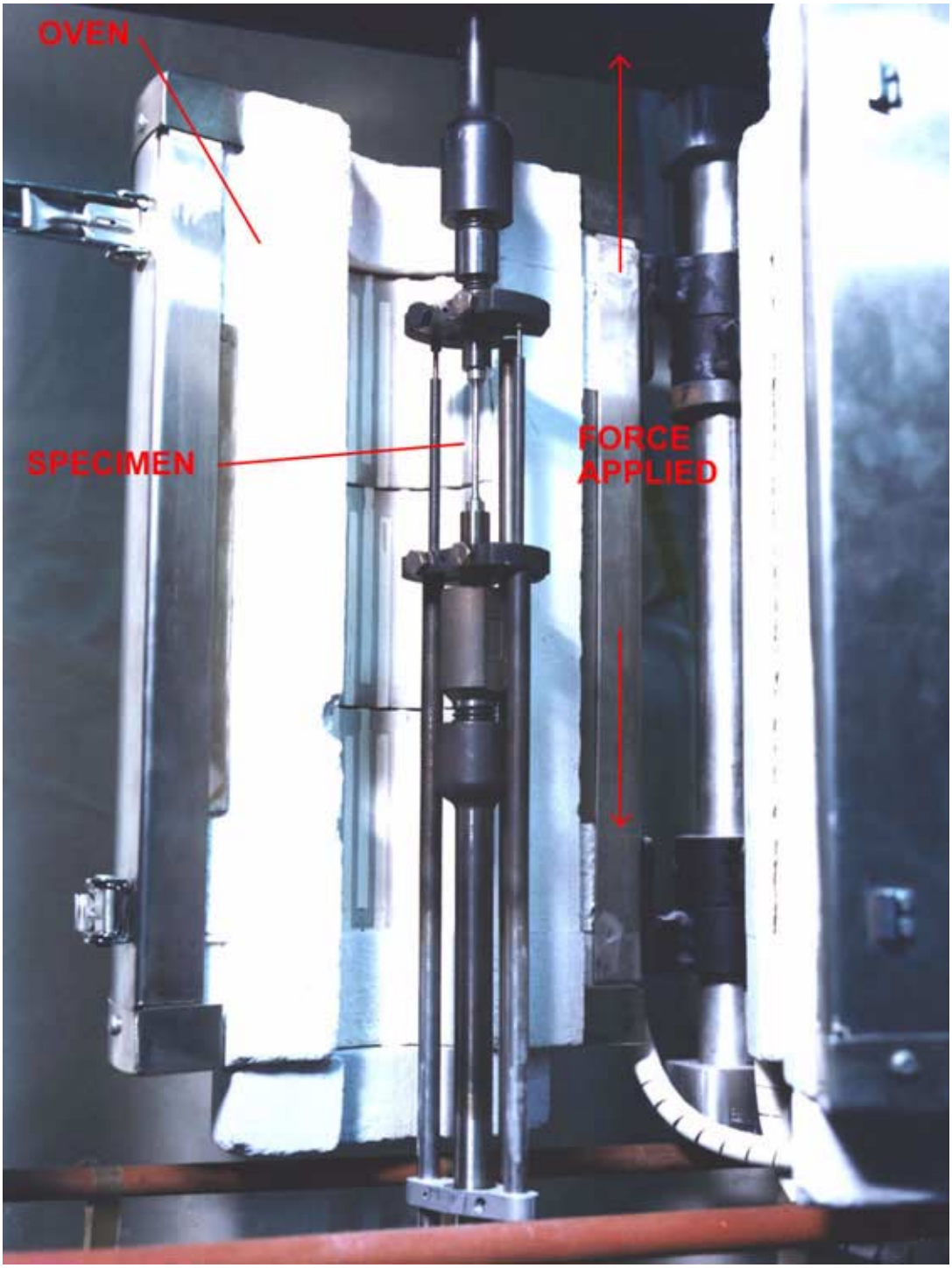

Exhibit 6-20 — Creep Test Stand

Exhibit 6-21 — Creep Test Specimens

Exhibit 6-22 is an example of a typical creep curve of total strain versus time. The initial strain ($\in_0$) occurs immediately when the load is applied. The curve generally exhibits three characteristic regions:

1. Primary Creep - In primary creep, the creep rate decreases due to initial strain hardening
2. Secondary Creep - Secondary creep is characterized by a relatively constant creep rate. It represents a kind of equilibrium situation in which the tendency to further strain harden is offset by annealing effects.
3. Tertiary Creep - Creep is accelerated due to necking and/or grain structure changes within the material (accumulation of voids at grain boundaries and grain boundary sliding). In a constant stress test, i.e., load reduced to maintain a constant stress as the specimen necks, tertiary creep may not occur.

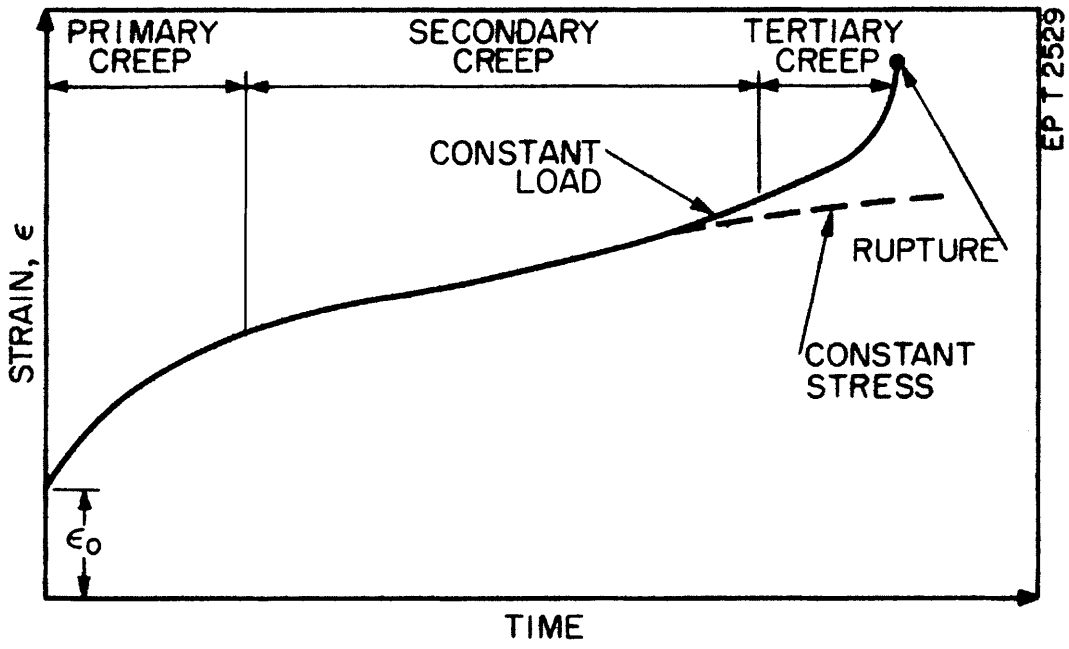

Exhibit 6-22 — Curve Of Three Stages Of Creep

6.3.5 — Fatigue

Fatigue of metals is the behavior of metals under the action of cyclic stress and strain, as opposed to steady stress and strain. Fatigue can be dangerous because a structure can be so weakened by a fatigue crack that complete fracture through the remaining cross-section occurs suddenly. Three basic factors related to stress are necessary to cause a fatigue failure:

- a tensile stress of sufficient magnitude
- a sufficient variation (range) of stress
- a sufficient number of cycles (fluctuations).

Fatigue failure is the failure mode of unflawed materials.

The fatigue life capability of a material can be determined by a series of fatigue tests run at different strain ranges. The resulting data is summarized by a fatigue curve, a plot of **stress amplitude (S)** versus the **cycles to failure (N)**, sometimes called an **S-N curve**. Some materials, including low alloy and plain carbon steels, have fatigue curves that flatten out at very high cycles ($>10^6$). The stress value at which this flattening out occurs is called the **endurance limit**.

Another type of fatigue test is the fatigue-crack-growth test. This test is conducted by subjecting a fatigue-cracked specimen (see Exhibit 6-15) to constant-amplitude cyclic-load fluctuations. The fatigue-crack length (a) is then measured and plotted against the number of load cycles (N) for various stress intensities (σ). The resulting plot is shown in Exhibit 6-23. A more useful presentation of fatigue-crack-growth data is to

plot the rate of fatigue-crack growth per cycle of load versus the stress intensity factor (ΔK_I) on a log-log plot as shown in Exhibit 6-24.

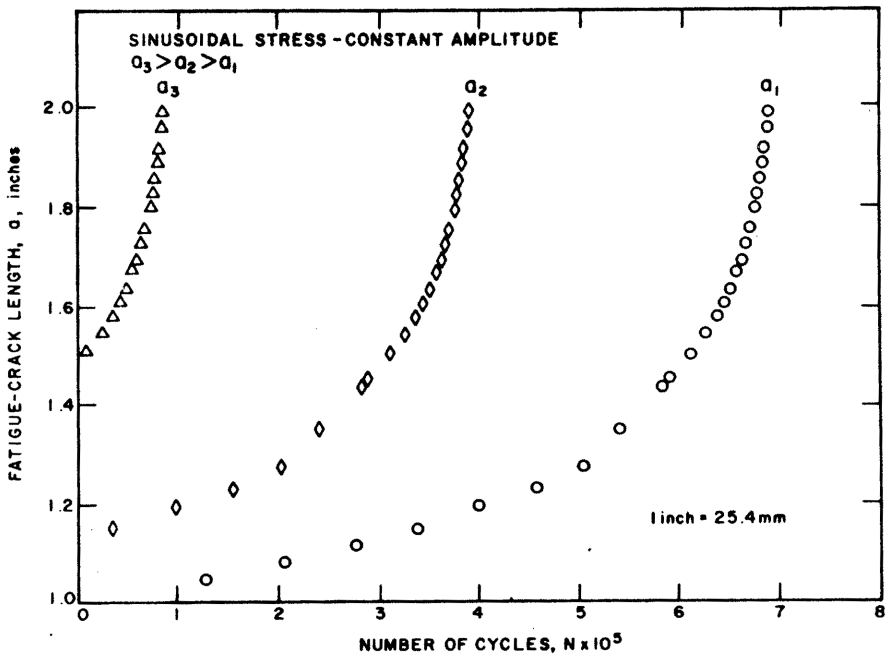

Exhibit 6-23 — a-N Curve

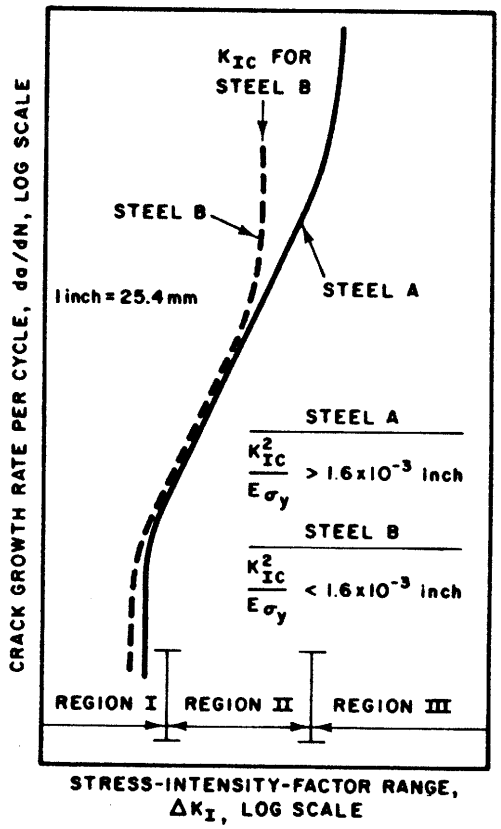

Exhibit 6-24 — Rate Of Crack-Growth Versus Stress Intensity Factor

The ability of a metal component to withstand many stress cycles depends on many factors in addition to the inherent strength of the material. Some factors, such as corrosive environments and temperature, are related to service conditions. Others, such as stress concentrations (e.g., notches, flaws) and metallurgical structural flaws can result from poor design, metallurgical, fabrication or handling practices. They must all be considered in reactor plant design. In addition, designers use a conservative design fatigue curve which is lower than the best fit of the experimental data. This conservative approach accounts not only for scatter in the test data but also for fabrication uncertainties.

Section 6.4 — Effects Of Irradiation On Metals

6.4.1 — Neutron Irradiation

Radiation exposure may alter the properties of metals used in reactor plant components by changing the arrangement of atoms in the metal's crystalline lattice. All radiation-induced changes in material properties are referred to as radiation damage, although not all of the resulting property changes are harmful. In fact, radiation can sometimes result in increased strength and fatigue life.

Of all the radiation emitted from a nuclear power plant, neutron irradiation is of primary concern. Gamma radiation will only generate heat in metals. Alpha, beta and fission product particles have too small of a range to be of a concern outside the core region (refer to Reference 1 for more details).

The initial kinetic energies of neutrons produced by fission have an average value of 2 MeV, but can exceed 10 MeV. Since neutrons are electrically neutral, they interact to a negligible extent with atomic orbital electrons and can travel well beyond the reactor core. A neutron's kinetic energy is dissipated by nuclear reactions (scattering or absorption) with atoms along its path, displacing atoms from their normal lattice sites and causing radiation damage in metal.

6.4.2 — Effects Due To Neutron Scattering Reactions

Most of the radiation damage caused by neutrons results from the scattering of fast neutrons. In scattering collisions with metallic atoms, the neutron retains most of its energy and moves on, having been deflected from its initial direction of travel. If the neutron's kinetic energy is less than some critical value the collision simply increases the struck atom's vibrational energy. If the neutron's kinetic energy exceeds this critical value the atom is ejected from its lattice position. This displaced atom, a **primary knock-on** atom, may strike other atoms with sufficient energy to dislodge them from their normal lattice sites, thus producing secondary, and higher order knock-on atoms. The critical energy to displace an atom is generally considered to be about 25 eV.

When an atom is knocked out of its normal lattice site, a void, or vacancy is created in the lattice structure. The moving atom then comes to rest some distance from its origin, either wedged between other atoms in normal lattice positions as an interstitial or in another lattice vacancy. The mobility of interstitial atoms at normal reactor operating temperatures is appreciable; therefore, many vacancies and interstitials recombine by diffusion or thermal activation. This process, called **microannealing**, reduces the damage to the lattice structure.

6.4.3 — The Effect Of Neutron Irradiation On The Mechanical Properties Of Metals

The effects of neutron irradiation on metals are similar to those of cold working. Neutron induced lattice defects impede slip, thereby increasing strength and decreasing ductility. Neutron irradiation also affects the brittle-to-ductile transition exhibited by body-centered cubic metals, such as low alloy ferritic steels.

In general, neutron exposure rate affects creep in metals in somewhat the same manner as elevated temperature. The concentration of vacancies during neutron radiation is greater than in the absence of a neutron flux by an amount established by the equilibrium between vacancy production rate and vacancy-interstitial recombination. Since an increased vacancy concentration promotes diffusion dependent phenomena, property changes associated with the increasing vacancy concentration produced by increasing temperature are also produced by exposure to high neutron fluxes. At elevated temperatures, the thermally produced vacancy concentration is so large that normally encountered levels of neutron radiation have a negligible effect. Thus, the greater the rate of neutron exposure, the greater the rate of creep deformation of a loaded component.

Refer to Reference 2 for additional effects and more information specific to reactor plant materials.

Section 6.5 — Iron And Steel Alloys

6.5.1 — Allotropes Of Iron

Iron changes crystal structure (allotropic changes) from one type of unit cell to another at fixed transition temperatures. Below 1670°F (910°C) iron is body-centered cubic (α iron), between 1670°F (910°C) and 2552°F (1394°C) it has a face-centered cubic (γ iron) structure. Above 2552°F (1394°C) the structure returns to body-centered cubic (δ iron). It remains a body-centered cubic (δ iron) up to 2800°F (1538°C), where it will melt. See Exhibit 6-25.

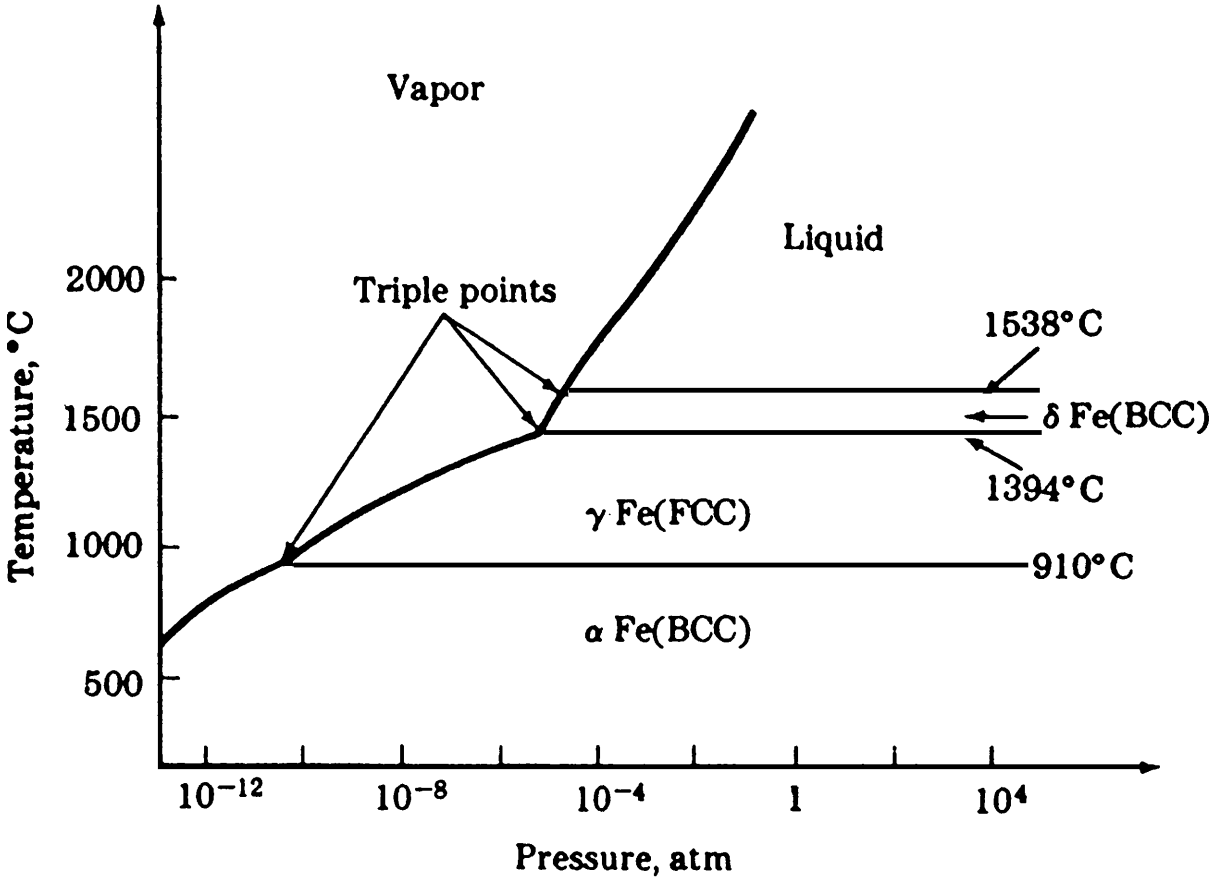

Exhibit 6-25 — Allotropic Changes Of Iron

6.5.2 — Classification Of Steels

Steels constitute a large percentage of structural materials. These iron based alloys can be divided into three broad categories:

- carbon steels
- low-alloy steels
- high alloy steels, such as stainless steels.

6.5.2.1 — Carbon Steels

Carbon steels contain small amounts of manganese (up to 0.9 w/o) and silicon (up to 0.3 w/o) whose principle function is to combine with oxygen and sulfur (commonly occurring impurities in steel) to reduce their harmful effects on the fracture toughness and ductile-to-brittle transition temperature. Carbon steels contain varying amounts of carbon, depending on their intended use. The final carbon content is the major determinant of the strength of these steels and their response to heat treatment. These alloys together with the unalloyed cast irons are the lowest in cost.

1. Low Carbon Steels - These steels contain up to approximately 0.2 w/o carbon. Because of the low carbon content it is not possible to increase hardness or strength by heat treatment. The strength of these steels is slightly greater than that of iron, but because of their strength properties, they are used for low strength boilerplates, structural supports, deck plates, and a number of general purpose applications. These steels are generally tough and ductile, and are easily formed, machined, and welded.
2. Medium Carbon Steels - These steels are stronger than the low carbon steels and can be strengthened further by heat treatment. They range in carbon content form approximately 0.2 w/o up to 0.45 w/o and are of higher strength than the low carbon steels. The medium carbon steels are used for piping systems in the secondary plant.
3. High Carbon Steels - These steels contain from 0.45 to over 1.0 w/o carbon. Hardness, strength, and ductility vary greatly over this range of carbon content. These steels find very limited use in power plant applications because the high carbon content reduces the ductility and makes fabrication such as forming, welding, and forging very difficult. These steels respond well to heat treatment but are susceptible to cracking during quenching and do not harden throughout except in thin sections. They are used for cutting tools, drills, and similar applications requiring high hardness.

6.5.2.2 — Low-Alloy Steels

Alloying elements such as chromium, manganese, molybdenum, and nickel improve strength, fracture toughness, corrosion, wear resistance, physical, and magnetic properties. Low-alloy steels have a carbon range of approximately 0.15 - 0.40 w/o. They contain up to a total of 5 w/o alloying elements which improve the hardening characteristics of carbon steels. Low-alloy steels have high strength, increased toughness, and greater resistance to abrasion and corrosion than carbon steels. Low-alloy steels, which are readily welded, are used to construct most of pressure vessels.

6.5.2.3 — High-Alloy Steels

These steels contain over 5 w/o alloying elements. One group of high-alloy steels (stainless steels) contain a large percentage of alloying elements to increase resistance to corrosion and improve high temperature strength. The two most important alloying elements in these steels are chromium and nickel. **Stainless steels** are used in many applications because of their excellent corrosion and oxidation resistance at elevated temperatures. Their corrosion resistance is due to a thin, tightly adherent chromium oxide film that protects the steel from most corroding media. This property is not evident in chromium steels until the chromium content is 12 w/o or more. For this reason, stainless steels contain at least 12 w/o chromium in addition to other alloying elements.

Some stainless steels can be heat treated to high strength while others cannot. The most common stainless steels are the Fe-18Cr-8Ni-0.08C (18-8) and the Fe-12Cr-0.10C alloys. The 18-8 stainless steel known as type

304 cannot be strengthened by heat treatment. However, on rapid cooling, Fe-12Cr-0.10C alloys (type 403 and type 410 stainless steels) form martensite which can be tempered to high strength.