SEP 10 1962

GENERAL ATOMIC

DIVISION OF **GENERAL DYNAMICS**

MASTER

GA-3410

EFFECT OF NEUTRON IRRADIATION ON MATERIALS
SUBJECTED TO MULTI-AXIAL STRESS DISTRIBUTIONS

QUARTERLY REPORT
FOR THE PERIOD ENDING
JUNE 30, 1962

U. S. Atomic Energy Commission
Contract AT(04-3)-167
Project Agreement 13

August 13, 1962

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

GENERAL ATOMIC
DIVISION OF
GENERAL DYNAMICS

JOHN JAY HOPKINS LABORATORY FOR PURE AND APPLIED SCIENCE

P.O. BOX 608, SAN DIEGO 12, CALIFORNIA

GA-3410

**EFFECT OF NEUTRON IRRADIATION ON MATERIALS
SUBJECTED TO MULTI-AXIAL STRESS DISTRIBUTIONS**

**QUARTERLY REPORT
FOR THE PERIOD ENDING
JUNE 30, 1962**

U. S. Atomic Energy Commission

Contract AT(04-3)-167

Project Agreement 13

by

T. A. Trozera

August 13, 1962

SUMMARY

This report presents the present status of the program "Effect of Neutron Irradiation on Materials Subjected to Multi-axial Stress Distributions." The program plan calls for the performance of tensile, notched tensile, tube, and Charpy tests on A-302B steel specimens both in the nonirradiated condition and irradiated to four flux levels. These tests will cover the temperature range from -50° to $+300^{\circ}$ F.

A capsule design has been finalized which uses the General Atomic developed Magneform* machine as the closure device.

A theoretical analysis of the critical conditions arising in a tube subjected to both internal pressure and axial load is presented. From this analysis one would expect instability to occur from an axial loading condition if the ratio of axial stress to circumferential stress were greater than two. An implication of the analysis is that one can predict, by means of a true stress-true strain curve and the proper equations, the strain, and hence the stress, at which a plastic instability is expected to occur.

BACKGROUND

Today the problem of materials in nuclear-reactor technology is quite well known to those people involved in the industry, and considerable effort has been devoted, especially in recent years, to research in the area of structural materials for nuclear reactors. Specifically, the effects of irradiation at various temperatures on such things as tensile strength, elongation, Charpy transition temperature, nil-ductility temperature, etc., are just a few of the many facets of interest to those who design reactors. Much of the past effort concerning the mechanical properties of structural materials for nuclear reactors has been in such areas as the Charpy and simple tension tests. This is understandable in view of the difficulty of performing tests in the hot cell, especially when one considers the problems of going into more involved testing, such as combined stress tests. In using past results, engineers have generally had to extrapolate simple tensile data into the realm of biaxial and, more generally, triaxial conditions; this has been done without knowledge of the range over which the parameters used are valid. It is the primary purpose of this investigation to undertake biaxial stress tests, over a range of temperatures, on tubes

*Trademark, General Dynamics Corporation.

which have been irradiated to various levels, and to compare these results with those obtained in simple tension tests on the same material in order to attempt to understand the range of validity over which flow parameters, such as the Von Mises-Hencky, may operate. In addition, Charpy and notched tensile tests are to be performed over the same range of temperatures in order to observe, in general, the fracture mechanics associated with the materials and the irradiation levels chosen.

PROGRAM

The program consists of four types of tests on specimens which have been subjected to four different integrated neutron fluxes over a temperature range from -50° to $+300^{\circ}$ F. The four tests are tensile, tube, notched tensile, and Charpy. The specimens will conform to ASTM standards for each type. In all cases the standard set of tests on the nonirradiated material over the temperature range to be used will be performed and used as a base line. Since it is the purpose of this program in part to make use of the various parameters that are in existence, it is necessary to perform tensile tests and to obtain from these the true stress-true strain characteristics of the material over a range of strains. Consequently, during the tests it will be necessary to observe both the reduction of diameter and the shape of the necked section in order to correct for the localized stresses existing in this region. It is planned to use a Bridgeman correction technique to correct for the stresses at the neck. A photographic method developed for a similar purpose will be used, if tests now in progress show it to be feasible. The most difficult portion of the program concerns the testing of tubes under combined tension and internal pressure. These tests become especially difficult in a hot cell, where complex instrumentation is out of the question. In view of this, clip gauges are being considered as a means of obtaining the radial strains, and it may be possible to obtain the longitudinal strains from cross-head motion. Tests are presently in progress to evaluate these two methods. It is felt that the Charpy and notched tensile tests are quite straightforward and require no special discussion.

Materials and Specimens

The material chosen for study is designated ASTM A-302 Grade B steel. A block of this material 6 in. by 6 in. by 12 in. has been obtained from Columbia-Geneva Steel Division of U. S. Steel Corporation. The heat number is A-0421, and this block is part of a reference heat whose past history has been closely followed. The material was austenized at 1650° F for 6 hr, quenched in water, stress-relieved at 1200° F for 6 hr, and air-cooled. The chemical composition has not yet been independently checked; however, alloying and impurity elements, in per cent, according

to available information are as follows: C, 0.24; Mn, 1.34; P, 0.011; S, 0.023; Si, 0.23; Ni, 0.18; Cr, 0.11; Mo, 0.51; Cu, 0.20; V,* <0.001; Ti, 0.015; B, 0.0001; Sn, 0.037; Cb, 0.004; Ta, 0.02; W,* <0.01; N, 0.008; Al (total), 0.04; Al (in solution), 0.002.

A cutting diagram has been prepared, and the material has been cut to ASTM standards. The tensile and impact specimens are to be tested in accordance with ASTM designation E184-61T. The tensile specimens (subsize) are to conform to ASTM designation E8, and the impact specimens are to conform to ASTM designation E23. Average grain size, which will be estimated according to ASTM designation E112, has not yet been determined.

Irradiations

Several capsule designs have been evaluated relative to cost, ease of fabrication, etc. At present two types of capsules are being considered: one type utilizes a tube, the other a can. In the tube-type capsule, the Magneform would be used to swage the aluminum tube over the samples. A cost comparison between this method and the next most economical method has been made. It is presently planned to enclose flux monitors--one to be supplied by Hanford as a standard set and a second to be supplied by General Atomic. In general, the program will follow suggestions as outlined by the Irradiation Standards Committee. Present plans call for irradiation in the Engineering Test Reactor at Idaho Falls, Idaho. Because of the expense involved, it is not presently planned to monitor the temperature during irradiation. However, melt wires will be incorporated into the capsule so that temperature ranges may be determined.

EXPERIMENTAL

The possibility of using cross-head motion of the tensile machine to create the necessary internal pressure for the tube tests has been studied. On the basis of several experiments performed on thin-wall stainless steel tubes, it appears possible to satisfactorily pressurize this material and strain it to rather large plastic strains (~ 0.20) when the cross-head motion is used to produce the pressure. The possibility of using this technique for producing simultaneously the required internal pressure and the axial tensile load was rejected on the basis of lead time necessary to both build and prove out a relatively untried device. A device capable of producing hydraulic pressures to 10,000 psi is available, and work is presently in progress to utilize this machine in the combined-stress tube tests. It is presently planned to adjust the internal pressure manually

* Estimated from spectrographic analysis.

and record the value as a function of strain. Devices for automatically programming pressures are available but are quite costly.

THEORETICAL

The following analysis will apply to the case of a thin-walled tube subjected to internal pressure and axial load in such a manner that the ratio of principal stresses may be kept constant during a test. It is assumed that the thickness is sufficiently small that the radial stresses can be neglected as compared with the stresses in the circumferential and longitudinal directions.

The analysis is of interest because it can indicate, within the realm of the assumptions made, the type of behavior to be expected under the above loading conditions and, hopefully, it may provide a basis for synthesizing the results of the tube tests with those of the simple tension test. The ultimate objective, of course, is to determine the range of validity over which flow parameters such as the Von Mises-Hencky operate in order to assist design engineers in their quest for information concerning the effects of more than a simple stress system on structural materials.

The symbols used in the analysis are as follows (see sketch below):

P = internal pressure
 L_A = axial load
 R = average radius of tube
 t = thickness of tube
 $\sigma_{\theta\theta}$ = circumferential stress
 σ_{rr} = radial stress

σ_{zz} = longitudinal stress
 ϵ_{ii} = true strain as indicated
 τ_{II} = deviator stress invariant equal to the normal true stress in a simple tensile test
 γ_{II} = deviator strain invariant equal to the true strain in a simple tension test

Under conditions of equilibrium,

$$2PR = 2\sigma_{\theta\theta}t; \quad \therefore \sigma_{\theta\theta} = \frac{PR}{t} \quad (1)$$

and

$$\sigma_{zz} = L_t / 2\pi R_t, \quad (2)$$

where $L_t = L_a + \pi R^2 P$; we assume that $\sigma_{rr} \cong 0$. The conditions for instability occur when either the pressure or the total load reaches a maximum.

Strain Conditions

Radial:

$$\epsilon_{rr} = \ln \frac{t}{t_0}; \quad t = t_0 e^{\epsilon_{rr}}. \quad (3)$$

Circumferential:

$$\epsilon_{\theta\theta} = \ln \frac{R}{R_0}; \quad R = R_0 e^{\epsilon_{\theta\theta}}. \quad (4)$$

From direct substitution of Eqs. (3) and (4) into Eqs. (1) and (2), one directly obtains the relationship between pressure and strains and load and strains:

$$P = \frac{\sigma_{\theta\theta} t_0 e^{(\epsilon_{rr} - \epsilon_{\theta\theta})}}{R_0}; \quad (5)$$

$$L_t = \sigma_{zz} 2\pi R_0 t_0 e^{(\epsilon_{\theta\theta} + \epsilon_{rr})}. \quad (6)$$

The Von Mises stress criterion can be expressed as

$$\tau_{II} = \sqrt{\frac{(\sigma_{rr} - \sigma_{\theta\theta})^2 + (\sigma_{\theta\theta} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{rr})^2}{2}}, \quad (7)$$

and if one assumes a constant ratio of normal stress to circumferential

stress in order to obtain a general solution

$$\frac{\sigma_{zz}}{\sigma_{\theta\theta}} = \alpha ,$$

then Eq. (7) becomes

$$\tau_{II} = \sigma_{\theta\theta} \sqrt{1 - \alpha + \alpha^2} . \quad (8)$$

Substituting Eq. (8) into Eq. (5) yields

$$P = \frac{\tau_{II0} e^{(\epsilon_{rr} - \epsilon_{\theta\theta})}}{\sqrt{1 - \alpha + \alpha^2} R_0} , \quad (9)$$

$$L_t = \frac{2\pi R_0 t_0 \alpha \tau_{II} e^{(\epsilon_{\theta\theta} + \epsilon_{rr})}}{\sqrt{1 - \alpha + \alpha^2}} . \quad (10)$$

Since the criteria for plastic instability occur when either the pressure or the load reaches a maximum, it is necessary to maximize Eqs. (9) and (10) with respect to the deviator strain, γ_{II} :

$$\frac{\partial P}{\partial \gamma_{II}} = 0 ; \quad \frac{\partial L_t}{\partial \gamma_{II}} = 0 .$$

From Eq. (9),

$$\frac{\partial P}{\partial \gamma_{II}} = \frac{\partial \tau}{\partial \gamma_{II}} e^{(\epsilon_{rr} - \epsilon_{\theta\theta})} + \tau_{II} e^{(\epsilon_{rr} - \epsilon_{\theta\theta})} \left\{ \frac{\partial \epsilon_{rr}}{\partial \gamma_{II}} - \frac{\partial \epsilon_{\theta\theta}}{\partial \gamma_{II}} \right\} = 0 ,$$

which reduces to

$$\frac{\partial \tau}{\partial \gamma_{II}} + \tau_{II} \left\{ \frac{\partial \epsilon_{rr}}{\partial \gamma_{II}} - \frac{\partial \epsilon_{\theta\theta}}{\partial \gamma_{II}} \right\} = 0 . \quad (11)$$

From Eq. (10),

$$\frac{\partial L_t}{\partial \gamma_{II}} = \frac{\partial \tau_{II}}{\partial \gamma_{II}} e^{(\epsilon_{\theta\theta} + \epsilon_{rr})} + \tau_{II} e^{(\epsilon_{\theta\theta} + \epsilon_{rr})} \left\{ \frac{\partial \epsilon_{rr}}{\partial \gamma_{II}} + \frac{\partial \epsilon_{\theta\theta}}{\partial \gamma_{II}} \right\} = 0,$$

which reduces to

$$\frac{\partial L_t}{\partial \gamma_{II}} = \frac{\partial \tau_{II}}{\partial \gamma_{II}} + \tau_{II} \left\{ \frac{\partial \epsilon_{rr}}{\partial \gamma_{II}} + \frac{\partial \epsilon_{\theta\theta}}{\partial \gamma_{II}} \right\} = 0. \quad (12)$$

The required relationship between the strains ϵ_{rr} , $\epsilon_{\theta\theta}$, and γ_{II} , the plastic deviator strain, is obtained from a consideration of the plastic stress-strain conditions:

$$\begin{aligned} \partial \epsilon_{rr} &= \frac{\partial \gamma_{II}}{\tau_{II}} \left\{ \sigma_{rr} - \frac{1}{2} (\sigma_{zz} + \sigma_{\theta\theta}) \right\} \\ \frac{\partial \epsilon_{rr}}{\partial \gamma_{II}} &= - \frac{\sigma_{\theta\theta} (\alpha + 1)}{2 \tau_{II}}; \end{aligned} \quad (13)$$

$$\begin{aligned} \partial \epsilon_{\theta\theta} &= \frac{\partial \gamma_{II}}{\tau_{II}} \left\{ \sigma_{\theta\theta} - \frac{1}{2} (\sigma_{rr} + \sigma_{zz}) \right\} \\ \frac{\partial \epsilon_{\theta\theta}}{\partial \gamma_{II}} &= \frac{\sigma_{\theta\theta}}{\tau_{II}} \left(1 - \frac{\alpha}{2} \right). \end{aligned} \quad (14)$$

Introduction of Eq. (8) into Eqs. (13) and (14) accomplishes the required elimination of $\sigma_{\theta\theta}$; hence,

$$\frac{\partial \epsilon_{rr}}{\partial \gamma_{II}} = - \frac{(\alpha + 1)}{2\sqrt{1 - \alpha + \alpha^2}}, \quad (15)$$

$$\frac{\partial \epsilon_{\theta\theta}}{\partial \gamma_{II}} = \frac{(2 - \alpha)}{2\sqrt{1 - \alpha + \alpha^2}}. \quad (16)$$

From the pressure criterion, Eq. (11),

$$\frac{\partial \ln \tau_{II}}{\partial \gamma_{II}} = \frac{3}{2\sqrt{1 - \alpha + \alpha^2}}, \quad (17)$$

and from the load criterion, Eq. (12),

$$\frac{\partial \ln \tau_{II}}{\partial \gamma_{II}} = \frac{2\alpha - 1}{2\sqrt{1 - \alpha + \alpha^2}}. \quad (18)$$

Since the true stress-true strain ($\tau_{II} - \gamma_{II}$) curves will be determined for steel and are known generally to fit the form

$$\tau_{II} = A \gamma_{II}^n, \quad (19)$$

where n is usually the strain at which necking occurs in tension, Eq. (17) may be reduced to

$$\gamma_{II} = \frac{2n\sqrt{1 - \alpha + \alpha^2}}{3}, \quad (20)$$

and Eq. (18) may be reduced to

$$\gamma_{II} = \frac{2n\sqrt{1 - \alpha + \alpha^2}}{2\alpha - 1}; \quad (21)$$

whichever is exceeded first is the condition at instability; hence, if $\alpha > 2$ one would expect instability to occur from an axial loading condition, whereas if $\alpha < 2$ one would expect instability to occur from a pressure condition.

In principle, one can predict, using Eq. (17) or Eq. (18) and a true stress-true strain curve for the material, the strain, and hence the stress, at which a plastic instability is expected to occur.