



U.S. NUCLEAR REGULATORY COMMISSION

LICINA

Revision 1
April 1977

REGULATORY GUIDE

OFFICE OF STANDARDS DEVELOPMENT

REGULATORY GUIDE 1.99

EFFECTS OF RESIDUAL ELEMENTS ON PREDICTED RADIATION DAMAGE TO REACTOR VESSEL MATERIALS

A. INTRODUCTION

General Design Criterion 31, "Fracture Prevention of Reactor Coolant Pressure Boundary," of Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Licensing of Production and Utilization Facilities," requires, in part, that the reactor coolant pressure boundary be designed with sufficient margin to ensure that, when stressed under operating, maintenance, testing, and postulated accident conditions, (1) the boundary behaves in a nonbrittle manner and (2) the probability of rapidly propagating fracture is minimized. Appendix G, "Fracture Toughness Requirements," and Appendix H, "Reactor Vessel Material Surveillance Program Requirements," which were added to 10 CFR Part 50 effective August 16, 1973, to implement, in part, Criterion 31, necessitate the prediction of the amount of radiation damage to the reactor vessel of water-cooled power reactors throughout its service life.

This guide describes general procedures acceptable to the NRC staff as an interim basis* for predicting the effects of the residual elements copper and phosphorus on neutron radiation damage to the low-alloy steels currently used for light-water-cooled reactor vessels. The Advisory Committee on Reactor Safeguards has been consulted concerning this guide and has concurred in the regulatory position.

**

B. DISCUSSION

The principal examples of NRC requirements that necessitate prediction of radiation damage are:

*Research and construction experience with low-residual-element compositions of these steels is accumulating rapidly and is expected to provide a firm basis for acceptable procedures in the near future.

**Lines indicate substantive changes from previous issue.

1. Paragraph II.H of Appendix G defines the beltline in terms of a predicted adjustment of reference temperature at end of service life in excess of 50°F; paragraphs III.C and IV.B specify the additional test requirements for beltline materials that supplement the requirements for reactor vessel materials generally.

2. Paragraph II.C.3 of Appendix H establishes the required number of surveillance capsules on the basis of the predicted adjusted reference temperature at the end of service life. In addition, withdrawal of the first capsule (when four or more are required) is to occur when the predicted adjustment of reference temperature is approximately 50°F or at one-fourth of the service life, whichever is earlier.

3. Paragraph IV.C of Appendix G requires that vessels be designed to permit a thermal annealing treatment if the predicted value of adjusted reference temperature exceeds 200°F during their service life.

4. Paragraph II.B of Appendix H incorporates ASTM E185-73 by reference. Paragraph 4.1 of ASTM E185-73 requires that the materials to be placed in surveillance be those that may limit operation of the reactor during its lifetime, i.e., those expected to have the highest adjusted reference temperature or the lowest Charpy upper-shelf energy at end of life. Both measures of radiation damage must be considered.

5. Paragraph V.B of Appendix G describes the basis for setting the upper limit for pressure as a function of temperature during heatup and cooldown for a given service period in terms of the predicted value of the adjusted reference temperature at the end of the service period.

The two measures of radiation damage used in this guide are obtained from the results of the Charpy V-

USNRC REGULATORY GUIDES

Regulatory Guides are issued to describe and make available to the public methods acceptable to the NRC staff of implementing specific parts of the Commission's regulations, to delineate techniques used by the staff in evaluating specific problems or postulated accidents, or to provide guidance to applicants. Regulatory Guides are not substitutes for regulations, and compliance with them is not required. Methods and solutions different from those set out in the guides will be acceptable if they provide a basis for the findings requisite to the issuance or continuance of a permit or license by the Commission.

Comments and suggestions for improvements in these guides are encouraged at all times and guides will be revised, as appropriate, to accommodate comments and to reflect new information or experience. This guide was revised as a result of substantive comments received from the public and additional staff review.

Comments should be sent to the Secretary of the Commission, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555, Attention: Docketing and Service Branch.

The guides are issued in the following ten broad divisions:

- | | |
|-----------------------------------|------------------------|
| 1. Power Reactors | 6. Products |
| 2. Research and Test Reactors | 7. Transportation |
| 3. Fuels and Materials Facilities | 8. Occupational Health |
| 4. Environmental and Siting | 9. Antitrust Review |
| 5. Materials and Plant Protection | 10. General |

Requests for single copies of issued guides (which may be reproduced) or for placement on an automatic distribution list for single copies of future guides in specific divisions should be made in writing to the U.S. Nuclear Regulatory Commission, Washington, D.C. 20555, Attention: Director, Division of Document Control.

notch impact test. Appendix G to 10 CFR Part 50 requires that a full curve of absorbed energy versus temperature be obtained through the ductile-to-brittle transition temperature region. The latter is located by the reference temperature, RT_{NDT} , which is defined in paragraph II.F of Appendix G. The "shift" of the adjusted reference temperature is defined in Appendix G as the temperature shift in the Charpy V-notch curve for the irradiated material relative to that for the unirradiated material, measured at the 50-foot-pound energy level or measured at the 35-mil lateral expansion level, whichever temperature shift is greater. In using published data that report only the temperature shift measured at the 30-foot-pound energy level, it has been assumed herein that the adjustment of the reference temperature is equal to the 30-foot-pound shift.

The second measure of radiation damage is the decrease in the Charpy upper-shelf energy level. In the absence of a standard definition, the upper-shelf energy is defined herein as the average energy value for all specimens whose test temperature is above the upper end of the transition temperature region. Normally, at least three specimens should be included; more specimens should be included when the shelf level appears to be marginal. However, if specimens are tested in sets of three at each test temperature, the set having the highest average may be regarded as defining the upper-shelf energy.

The measure of fluence used herein is the number of neutrons per square centimeter ($E > 1 \text{ MeV}$). An assumed fission-spectrum energy distribution was used in calculating the fluence for most of the data base.* However, for application to a reactor vessel, the calculated spectrum is used to predict fluence at a given location in the wall. This procedure is not intended to preclude future use of data that are given in terms of neutron damage fluence.

As used herein, references to "% Cu" and "% P" mean the weight percent of copper and phosphorus as measured in the surveillance program per ASTM E185-73. However, if such results are not available, the results of a product analysis may be used.

Use of the procedures for prediction of radiation damage given in the regulatory position should be limited to irradiation at $550 \pm 25^\circ\text{F}$, because temperature is important to damage recovery processes. As a guideline, irradiation at 450°F has been shown to cause twice the adjustment of reference temperature and irradiation at 650°F , about half the adjustment produced by irradiation at 550°F for the fluence levels and the steels cited in the regulatory

*The data base for this guide is that given by Spencer H. Bush, "Structural Materials for Nuclear Power Plants," 1974 ASTM Gillett Memorial Lecture, published in ASTM Journal of Testing and Evaluation, Nov. 1974, and its addendum, "Radiation Damage in Pressure Vessel Steels for Commercial Light-Water Reactors."

position when the copper content is about 0.15%. The effects of irradiation temperature on decrease in shelf energy should be considered qualitatively similar to those cited for the adjustment of reference temperature.

Sensitivity to neutron embrittlement may be affected by other residual elements such as vanadium and by deoxidation practice, as indicated by the findings of current research. In predicting radiation damage for materials that differ in chemical content or deoxidation practice from those that make up the data base, such findings should be considered. Other residual elements, notably sulfur, impair the initial Charpy shelf energy of these materials, and their content should be kept low. Clearly, it is the remaining toughness at end of life or at some other critical period that is important. Such toughness may be given in terms of the margin between the operating temperature (nominally 550°F) and the limiting temperature based on toughness. A margin of 200 degrees is desirable to permit safe management of system transients. At full power, the limiting temperature based on toughness is generally 150-200 degrees above RT_{NDT} ; hence, the latter should not exceed $150\text{-}200^\circ\text{F}$ at end of life. This limit also avoids the problems of providing for annealing, per paragraph IV.C of Appendix G. The levels of residual elements such as copper, phosphorus, sulfur, and vanadium that are required to achieve the limit of 200°F adjusted reference temperature at end of life in a given reactor vessel will depend on the initial values of RT_{NDT} of the beltline materials and on the predicted fluence at the particular locations in the vessel where the materials are used.

When surveillance data from the reactor in question become available, the weight given to it relative to the information in this guide should depend on the credibility of the surveillance data as judged by the following criteria:

1. Materials in the capsule should be those judged most likely to be controlling with regard to radiation damage according to the provisions of this guide.
2. Scatter in the Charpy data should be small enough to avoid large uncertainty in curve fitting.
3. The change in yield strength should be consistent with the shift in the Charpy curve.
4. The relationship to previous surveillance data from the same reactor should be consistent with the normal trends of such data.
5. The surveillance data for the correlation monitor material in the capsule should fall within the scatter band of the data base for that material.

C. REGULATORY POSITION

1. When credible surveillance data from the reactor in question are not available, prediction of neutron radiation damage to the beltline of reactor vessels of light water reactors should be based on the following procedures.

a. Reference temperature should be adjusted as a function of fluence and residual element content in accordance with the following expression, within the limits below and in paragraph 1.c.

$$A = [40 + 1000(\% \text{ Cu} - 0.08) + 5000 (\% \text{ P} - 0.008)] [f/10^{19}]^{1/2}$$

where

A = predicted adjustment of reference temperature, °F.

f = fluence, n/cm² (E>1 MeV).

% Cu = weight percent of copper.
If % Cu ≤ 0.08. use 0.08.

% P = weight percent of phosphorus .
If % P ≤ 0.008. use 0.008.

If the value of A obtained by the above expression exceeds that given by the curve labeled "Upper Limit" in Figure 1, the "Upper Limit" curve should be used. If % Cu is unknown, the "Upper Limit" curve should be used.

As illustrated in Figure 1 for selected copper and phosphorus contents, the above expression should be considered valid only for A > 50°F and for f < 6 x 10¹⁹ n/cm² (E > 1 MeV).

b. Charpy upper-shelf energy should be assumed to decrease as a function of fluence and copper content as indicated in Figure 2. within the limits listed in paragraph 1.c. Interpolation is permitted.

c. Application of the foregoing procedures should be subject to the following limitations:

(1) The procedures apply to those grades of SA-302, 336, 533, and 508 steels having minimum specified yield strengths of 50,000 psi and under and to their welds and heat-affected zones.

(2) The procedures are valid for a nominal irradiation temperature of 550°F. Irradiation below 525°F should be considered to produce greater damage and irradiation above 575°F may be considered to produce less damage. The correction factor used should be justified.

(3) The expression for A is given in terms of fluence as measured by units of n/cm² (E > 1 MeV) however, the expression may be used in terms of fluence as measured by units of neutron damage fluence, provided the constant 10¹⁹ n/cm² (E > 1 MeV) is changed to the corresponding value of neutron damage fluence.

(4) Application of these procedures to materials having chemical content beyond that represented by the current data base should be justified by submittal of data.

2. When credible surveillance data from the reactor in question become available, they may be used to represent the adjusted reference temperature and the Charpy upper-shelf energy of the beltline materials at the fluence received by the surveillance specimens.

a. The adjusted reference temperature of the beltline materials at other fluences may be predicted by:

(1) extrapolation to higher or lower fluences from credible surveillance data following the slope of the family of lines in Figure 1 or

(2) a straight-line interpolation between credible data on a logarithmic plot.

b. To predict the decrease in upper-shelf energy of the beltline materials at fluences other than those received by the surveillance specimens, procedures similar to those given in paragraph 2.a may be followed using Figure 2.

3. For new plants, the reactor vessel beltline materials should have the content of residual elements such as copper, phosphorus, sulfur, and vanadium controlled to low levels. The levels should be such that the predicted adjusted reference temperature at the ¼ T position in the vessel wall at end of life is less than 200°F.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for utilizing this regulatory guide

This guide reflects current regulatory practice. Therefore, except in those cases in which the applicant proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the positions described in this guide will be used by the NRC staff as follows:

1. The method described in regulatory positions C.1 and C.2 of this guide will be used in evaluating all predictions of radiation damage called for in Appendices G and H to 10 CFR Part 50 submitted on or

C. REGULATORY POSITION

1. When credible surveillance data from the reactor in question are not available, prediction of neutron radiation damage to the beltline of reactor vessels of light water reactors should be based on the following procedures.

a. Reference temperature should be adjusted as a function of fluence and residual element content in accordance with the following expression, within the limits below and in paragraph 1.c.

$$A = [40 + 1000(\% \text{ Cu} - 0.08) + 5000(\% \text{ P} - 0.008)] [f/10^{19}]^{1/2}$$

where

A = predicted adjustment of reference temperature, °F.

f = fluence, n/cm² (E > 1 MeV).

% Cu = weight percent of copper.
If % Cu ≤ 0.08, use 0.08.

% P = weight percent of phosphorus.
If % P ≤ 0.008, use 0.008.

If the value of A obtained by the above expression exceeds that given by the curve labeled "Upper Limit" in Figure 1, the "Upper Limit" curve should be used. If % Cu is unknown, the "Upper Limit" curve should be used.

As illustrated in Figure 1 for selected copper and phosphorus contents, the above expression should be considered valid only for A > 50°F and for f < 6 x 10¹⁹ n/cm² (E > 1 MeV).

b. Charpy upper-shelf energy should be assumed to decrease as a function of fluence and copper content as indicated in Figure 2, within the limits listed in paragraph 1.c. Interpolation is permitted.

c. Application of the foregoing procedures should be subject to the following limitations:

(1) The procedures apply to those grades of SA-302, 336, 533, and 508 steels having minimum specified yield strengths of 50,000 psi and under and to their welds and heat-affected zones.

(2) The procedures are valid for a nominal irradiation temperature of 550°F. Irradiation below 525°F should be considered to produce greater damage, and irradiation above 575°F may be considered to produce less damage. The correction factor used should be justified.

(3) The expression for A is given in terms of fluence as measured by units of n/cm² (E > 1 MeV); however, the expression may be used in terms of fluence as measured by units of neutron damage fluence, provided the constant 10¹⁹ n/cm² (E > 1 MeV) is changed to the corresponding value of neutron damage fluence.

(4) Application of these procedures to materials having chemical content beyond that represented by the current data base should be justified by submittal of data.

2. When credible surveillance data from the reactor in question become available, they may be used to represent the adjusted reference temperature and the Charpy upper-shelf energy of the beltline materials at the fluence received by the surveillance specimens.

a. The adjusted reference temperature of the beltline materials at other fluences may be predicted by:

(1) extrapolation to higher or lower fluences from credible surveillance data following the slope of the family of lines in Figure 1 or

(2) a straight-line interpolation between credible data on a logarithmic plot.

b. To predict the decrease in upper-shelf energy of the beltline materials at fluences other than those received by the surveillance specimens, procedures similar to those given in paragraph 2.a may be followed using Figure 2.

3. For new plants, the reactor vessel beltline materials should have the content of residual elements such as copper, phosphorus, sulfur, and vanadium controlled to low levels. The levels should be such that the predicted adjusted reference temperature at the 1/4T position in the vessel wall at end of life is less than 200°F.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for utilizing this regulatory guide.

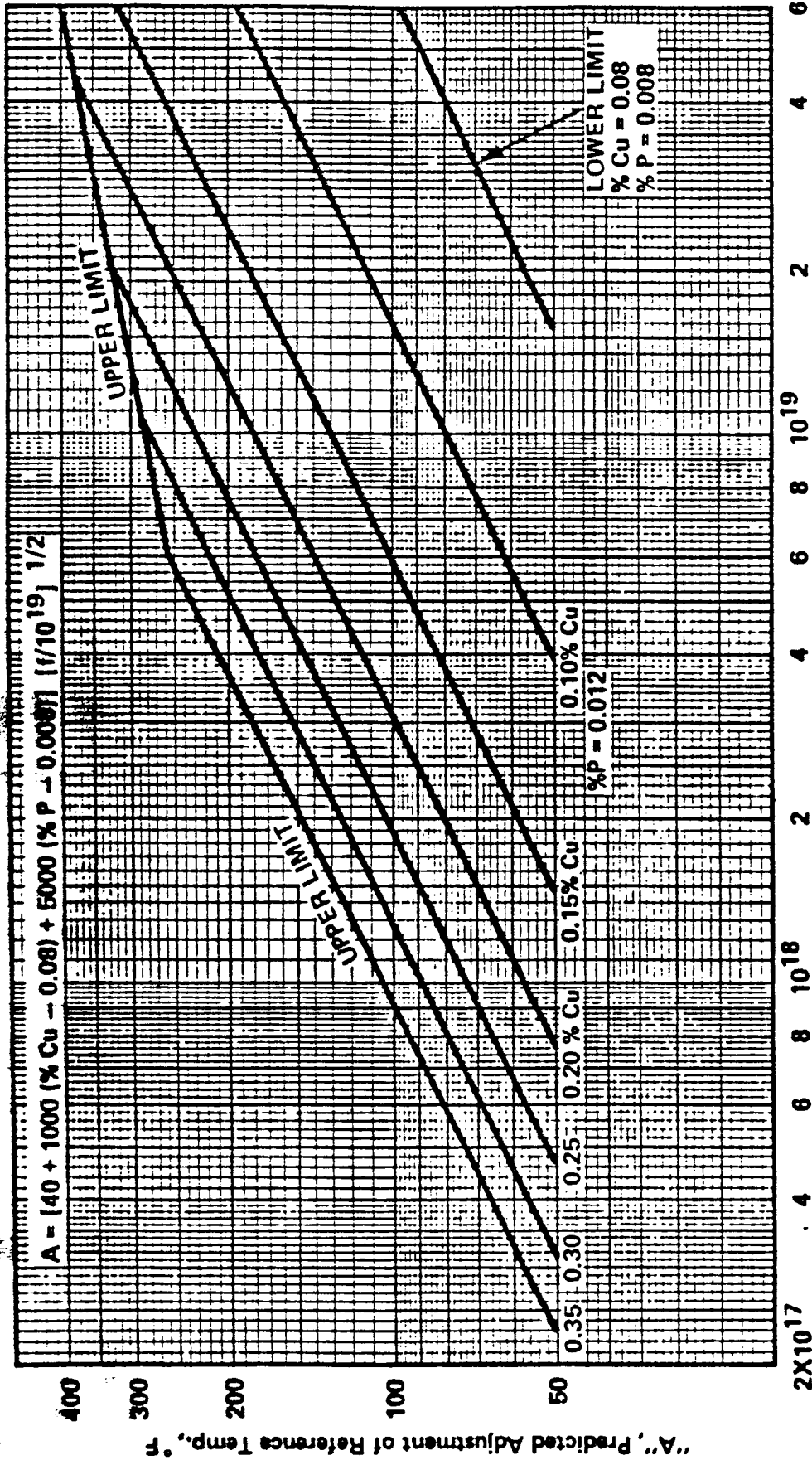
This guide reflects current regulatory practice. Therefore, except in those cases in which the applicant proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the positions described in this guide will be used by the NRC staff as follows:

1. The method described in regulatory positions C.1 and C.2 of this guide will be used in evaluating all predictions of radiation damage called for in Appendices G and H to 10 CFR Part 50 submitted on or

after June 1, 1977; however, if an applicant wishes to use the recommendations of regulatory positions C.1 and C.2 in developing submittals before June 1, 1977, the pertinent portions of the submittal will be evaluated on the basis of this guide.

2. The recommendations of regulatory position C.3 will be used in evaluating construction permit ap-

plications docketed on or after June 1, 1977; however, if an applicant whose application for construction permit is docketed before June 1, 1977, wishes to use the recommendations of regulatory position C.3 of this regulatory guide in developing submittals for the application, the pertinent portions of the application will be evaluated on the basis of this guide.



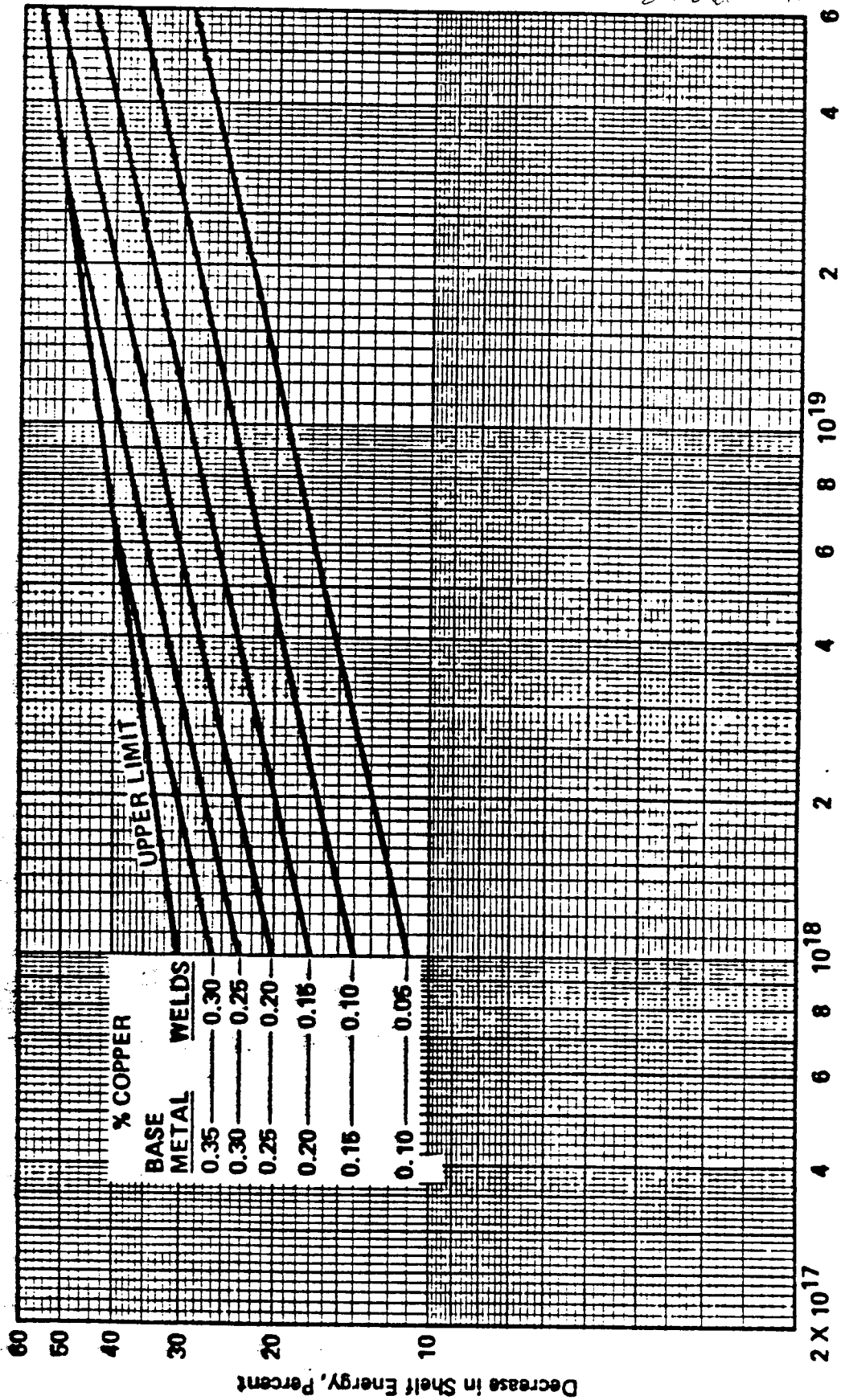
From July, 1975
revision.
Should be the same as Rev.

Figure 1 Predicted Adjustment of Reference Temperature, "A", as a Function of Fluence and Copper Content. For Copper and Phosphorus Contents Other Than Those Plotted, Use the Expression for "A" Given on the Figure.

From July, 1975 revision

Should be the same as

Rev. 1 (E)
Rev. 2 (E)



FLUENCE, n/cm² (E > 1 MeV)

Figure 2 Predicted Decrease in Shelf Energy as a Function of Copper Content and Fluence.