CAROLINA POWER AND LIGHT COMPANY

SHEARON HARRIS NUCLEAR POWER PLANT

FUNCTIONAL CAPABILITY OF ASME CLASS 1 AUXILIARY PIPING SYSTEMS

RESPONSE TO SHNPP SER OPEN ITEM (3)

MAY, 1984

REVISION 1 - August, 1984

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New York, NY 10048

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TABLE OF CONTENTS

CAROLINA POWER AND LIGHT COMPANY
SHEARON HARRIS NUCLEAR POWER PLANT
FUNCTIONAL CAPABILITY OF ASME CLASS 1
AUXILIARY PIPING SYSTEMS

LIST OF FIGURES AND TABLES

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FUNCTIONAL CAPABILITY OF ASME CLASS 1
AUXILIARY PIPING SYSTEMS

PREFACE

This report was prepared in response to SHNPP SER Open Item #(3) and presents the methodology and evaluation criteria which demonstrate the functional capability of Class 1 auxiliary piping as required by USNRC SRP 3.9.3 Appendix A (NUREG-0800, July 1981). (4)

SHNPP SER Section 3.9.3.1

SER Open Item #(3) Functional Capability of Class 1 Auxiliary Piping Systems

- "For ASME Class 1 auxiliary piping systems, the applicant has used a stress limit of 3.0 Sm, as stated in Appendix F of the ASME Code, (1) Section III, for use in equation (9) of Paragraph NB-3652. The faulted limit used by the applicant is intended to ensure structural integrity and not the functional capability of the piping system. The applicant believes that these limits provide assurance that the piping will not collapse or experience gross distortion and, thus, will not cause a loss of capability to perform their safety function. The staff has not accepted the justification provided by the applicant and considers this item open."

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1.0 ABSTRACT

Functional capability of piping components is defined as the capability to deliver rated flow and retain dimensional stability when the design and service loads, and their resulting stresses and strains, are at prescribed levels. This report presents the methodology, evaluation and acceptance criteria used in demonstrating the functional capability of Class 1 auxiliary piping systems. The scope of this report is limited to the evaluation of <u>essential Class 1 auxiliary piping</u> for the Shearon Harris Nuclear Power Plant.

Generically, the issue of functional capability for piping was not identified as an NRC concern until July 1981, when the NRC issued NUREG-0800 which included SRP 3.9.3(4) and its Appendix A, the acceptance criteria adopted by the NRC for functional piping. Almost simultaneously, the NRC approved NEDO-21985(3) as an acceptable basis of demonstrating functional capability. Prior to the NRC's adoption of these criteria, passive components in essential systems were considered operable if they met the pressure integrity considerations of the ASME code pursuant to Regulatory Guide 1.48(8). NEDO-21985 presents criteria for evaluation of functional capability to be used in conjunction with elastic analysis of piping systems. It specifically recognizes that more sophisticated techniques such as elastic plastic analysis may be employed to reduce the conservatism resulting from NEDO-21985 criteria.

The criteria presented herein make use of equations and definitions given in the ASME Code and are principally based upon inelastic analysis techniques. A deformation limit in terms of an ultimate moment for different pipe sizes is established. The limit was selected such that small reductions in the cross-sectional area are assured. The reduction in cross-sectional area is given in terms of ovalization which indicates the formation of an eliptical shape

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Definitions and Nomenclature of <u>underlined</u> terms and phrases are presented in Section 4.0

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AUXILIARY PIPING SYSTEMS

2.0 INTRODUCTION

Piping systems and components essential to plant safety should be capable of delivering rated flow and retain dimensional stability when the design and service loads, and their resulting stresses and strains, are at prescribed levels. The ability to do this is termed functional capability. A piping system might lose its functional capability through the occurrence of a significantly reduced flow area.

The ASME Boiler and Pressure Vessel Code Section III provides rules for piping design and analysis for Class 1 piping systems in Sub section NB. While Code rules provide levels of allowable stress limits to assure pressure retention capability, they may not assure the functional capability of certain system components under all designated loading conditions.

In the past, the question of functional capability was addressed by selecting conservative stress limits usually presented by multiples of the yield strength of materials. In addition, elastic analysis techniques are generally employed.

The techniques employed in this report utilize inelastic methods of piping analyses and establish deformation limits such that small reductions in pipe cross-sectional area are assured. Finite element analyses of three dimensionally modeled elbows (shell elements), with elasto-plastic strain hardening material properties and with large deformation considerations are conducted. The functional capability of essential piping is evaluated by computing the ovalization and resulting percentage change in flow area for different values of moments applied up to failure.

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FUNCTIONAL CAPABILITY OF ASME CLASS 1
AUXILIARY PIPING SYSTEMS

3.0 SCOPE

The scope covered by the methodology, and evaluation criteria presented in this report is limited to Reactor Coolant Systems (RCS), essential Class 1 auxiliary piping components. The analytical approach is to perform an analysis for elbows and extend the results to other piping components by appropriate techniques.

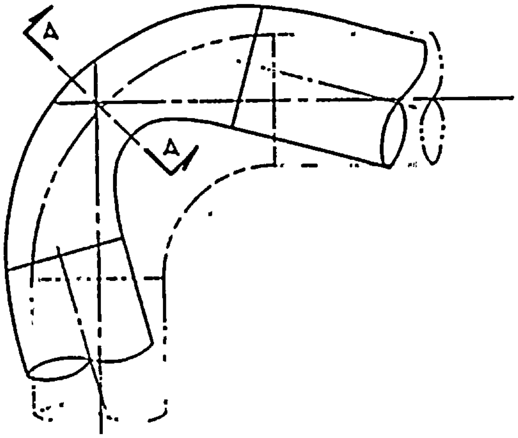
The piping of the RCS is required to maintain its functionability as well as structural integrity under all loading conditions including the Level D loading. In essence, the piping is required to retain dimensional stability such that it will deliver its rated flow. Under Level D loading, the piping may undergo permanent plastic deformation as depicted from the ASME Code allowables being $3S_m$ or $0.7S_u$ and, therefore, plastic analyses are required to ascertain the piping deformation under the level D loadings.

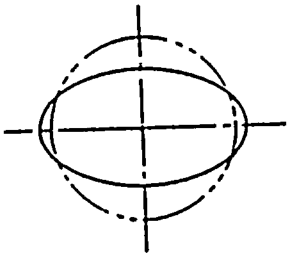
Table I presents a summary of the RCS Class 1 auxiliary piping to be evaluated for functional capability. A total of five (5) Class 1 auxiliary pipe sizes ranging from 1-1/2" to 14" in diameter were considered.

4.0 NOMENCLATURE & DEFINITIONS

4.1 Ovalization indicates the formation of an elipsoidal cross section as depicted below

Ovalization, δD, is the maximum decrease in the elbow diameter as it deforms into an elliptical shape.





SECT. A-A

4.2 Percent ovalization = $\frac{\delta D}{D} \times 100 = \frac{Di-A}{D_{nominal}} \times 100$

4.3 Percent change in Area, $\frac{\delta A}{A} \times 100 = \frac{\pi \times A \times B/4 - (\pi Di^2)/4 \times 100}{\pi (Di^2)/4}$

where,

Di = inside diameter of the elbow cross section
A = Minimum inside diameter of the deformed shape
B = Maximum inside diameter of the deformed shape
D = Nominal size of the pipe

4.0 NOMENCLATURE & DEFINITIONS (Cont'd)

4.4 θ is the enforced rotation of the ends of the elbow

4.5 M is the moment resisted by the elbow

4.6 Instability moment, M_I is the moment at which the moment resistance decreases for an increased rotation, i.e. the moment at which the tangent to the M-θ curve is horizontal.

4.7 B2 is the stress index as per ASME Section III NB 3650 Equation 9, that accounts for the reduction of the moment carrying capacity of a fitting or weld.

4.8 ε_y yield strain = .002 X $\frac{Sy}{E}$, and Sy is the yield stress.

4.9 t is the pipe thickness

4.10 R is the pipe nominal radius

4.11 Shape factor - the ratio between the plastic section modulus and the elastic section modulus

4.12 Mult (Gerber) = the ultimate moment calculated on the basis of the strain power law [Ref. 2].

4.13 Functional Capability - Ability of a component, including its supports, to deliver rated flow and retain dimensional stability when the design and service loads, and their resulting stresses and strains, are at prescribed levels.

4.0 NOMENCLATURE & DEFINITIONS (Cont'd)

4.14 Design Limits - The limits for the design loadings provided in the appropriate subsection of Section III, Division 1, of the ASME Code.

4.15 Design Loads - Those pressures, temperatures, and mechanical loads selected as the basis for the design of a component.

4.16 Functional System - That configuration of components which, irrespective of ASME Code Class designation or combination of ASME Code Class designations, performs a particular function (i.e., each emergency core cooling system performs a single particular function and yet each may be comprised of some components which are ASME Class 1 and other components which are ASME Code Class 2).

4.17 LOCA - Loss of Coolant Accidents - Defined in Appendix A of 10CFR Part 50 as "those postulated accidents that result from the loss of reactor coolant, at a rate in excess of the capability of the reactor coolant makeup system, from breaks in the reactor coolant pressure boundary, up to and including a break equivalent in size to the double-ended rupture of the largest pipe of the reactor coolant system."

This condition includes the loads from the postulated pipe break, itself, and also any associated system transients or dynamic effects resulting from the postulated pipe break.

4.18 MS/FWPB - Main Steam and Feedwater Pipe Breaks - Postulated breaks in the main steam and feedwater lines.

4.0 NOMENCLATURE & DEFINITIONS (Cont'd)

4.19 Piping Components - These items of a piping system such as tees, elbows, bends, pipe and tubing, and branch connections constructed in accordance with the rules of Section III of the ASME Code.

4.20 Postulated Design Basis Events - Those postulated natural phenomena (i.e., OBE, SSE), postulated site hazards, (i.e., nearby explosion), or postulated plant events (i.e., DBPB, LOCA, MS/FWPB) for which the plant is designed to survive without undue risk to the health and safety of the public.

4.21 SSE - Safe Shutdown Earthquake - Defined in Section III(c) of Appendix A of 10CFR Part 100.

4.22 Service Limits - The four limits for the service loading as provided in the appropriate subsection of Section III, Division 1, of the ASME Code; Level A (Normal), Level B (Upset), Level C (Emergency), Level D (Faulted).

4.23 Service Loads - Those pressure, temperature, and mechanical loads provided in the Design Specification.

4.24 Essential Class 1 Auxiliary Piping - Piping and piping components required to shutdown the reactor and mitigate the consequences of a postulated design basis accident by transporting a specified quantity of fluid from one point to another point, with a specified pressure drop between the two points.

5.0 METHODOLOGY

5.1 Loading and Modeling Approach

5.1.1 Introduction:

The application of shear and normal forces and out of plane and torsional moments on elbows do not result in any appreciable ovalization. Therefore, for a certain level of stresses in the elbow the highest ovalization is attained when the stresses are attributable to in plane bending. Henceforth, in this study pure bending is applied on the ends of the elbow, and in order to assure the condition of pure bending the ends of the piping on each side of the elbow are unconstrained.

5.1.2 Loading:

A pure bending moment is applied on each of the unrestrained ends of the elbow. The direction of moment is such that it produces tensile stresses on the concave side of the elbow (closing moment), see Fig. (1).

The elbow is loaded via enforced rotation of its ends which is monotonically increased until failure takes place at the elbow.

5.1.3 Model:

A model of a 90° elbow of radius 1.5D with two straight pipe segments of length 4D on each end is considered in this study. The reason for using the straight segment of the pipe is twofold. First is to provide a sufficient zone for the plastic hinge to develop about the center (45° plane) of the elbow, and second is to set the location of the loading point with its inherent assumptions (small linear displacement and elastic stress distribution) remote from the center of the plastic hinge. See Fig.(1).

5.0 METHODOLOGY (Cont'd)

5.1 Loading and Modeling Approach (Cont'd)

5.1.4 Finite Element Code:

The MSC-NASTRAN [Ref. 7] Version 63 Code, Solution 66 is implemented to conduct the elasto-plastic large deformation analysis of the elbows.

5.1.5 Boundary Conditions:

For the pure moment loading of the elbow in its plane of curvature, two planes of symmetry exist.

1. 45° plane of the elbow, normal to the centerline of the piping, i.e. symmetry about the piping mid-length.
2. 0-180° plane of the cross section containing the centerline of the piping, i.e. symmetry about the plane of curvature of the elbow.

Therefore, both conditions of symmetry are utilized to reduce the model to 1/4 its original size.

Free boundaries are provided for the end points at which the rotations are applied.

6.0 DESCRIPTION OF THE FINITE ELEMENT MODEL

Twelve (12) equal shell elements are used to describe the 180° segment of the pipe cross section in the circumferential direction. Along the length of the straight segment of the piping, 5 subdivisions are used, the first three from the free end length = D, the fourth and fifth are of length 2D/3 and D/3 respectively. Along the elbow 9 closely spaced subdivisions are used (5° each). Therefore, a total of 168 (12 x 14) shell elements, connecting a total of 195 grid points (15 x 13) are used to describe the 1/4 model, [figures 1b and 1c].

A rigid body element is used to connect the grid points on the free end of the elbow such that when the moment is applied at the center of the cross section, a linear elastic stress distribution develops at the free pipe cross section.

6.1 Material Properties:

A stress-strain curve of elasto-plastic strain hardening properties is used to describe the shell elements material properties, [Figure 2]. The curve is digitized from the strain power law ($S = S_o \varepsilon^n$) in the plastic region, whereas in the elastic region the modulus of elasticity as per ASME Code is used. The constants n and S_o are determined from the equations:

$$n = L_n (1 + \varepsilon_u)$$

$$S_u = S_o (\varepsilon_u)^n$$

An approach that is widely used in the Literature, (2, 9, 12) which is proven to render excellent match of the experimental stress strain data (12). The ultimate stress S_u and the ultimate strain ε_u are extracted for the material at the temperature from Ref. (10) and (11).

6.0 DESCRIPTION OF THE FINITE ELEMENT MODEL (Cont'd)

6.1 Material Properties: (Cont'd)

Stainless steel material A-376-304 and A-376-316 are used in this analysis, for which the following parameters are given:

	So (psi)	n	E(psi)	ε_u	Su(psi)	Sm(psi)	Sy(psi)
A-376-304	78,023	0.1865	25.5×10^6	0.205	58,058	16,200	20,400
A-376-316	89,014	0.2056	25.5×10^6	0.2283	65,700	16,700	20.500

6.2 Yield Criterion:

The von-Misses yield criterion is used to represent the state of the stresses within each element, the equivalent stress of which is given by:

$$S_{equ} = \sqrt{1/2\ [(S_1-S_2)^2 + (S_2-S_3)^2 + (S_3-S_1)^2]}$$

where

S_1, S_2, S_3 are the three principal stresses.

Failure of the material is postulated when the equivalent stress as computed by von-Misses stress criteria exceeds the ultimate stress as defined in the stress-strain curve used.

6.0 DESCRIPTION OF THE FINITE ELEMENT MODEL (Cont'd)

6.3 Large Deformation:

A large deformation feature is utilized in order to account for the effect of the ovalization of the pipe cross section on the moment carrying capacity of the elbow. The cross sectional ovalization reduces the pipe section modulus, i.e. reduces the value of Moment/max stress. The moment may still be increasing due to the plastic flow which allows greater portions of the cross section to be subjected to higher stresses.

7.0 RESULTS

The M-θ curves are obtained for all elbows of the pipe sizes listed in Table 1, and are given in Figs. 3 through 7. Typical deformation shapes and stress distribution are given in Figs. 7 through 10. On the M-θ curves, scales of % ovalization and % change in cross sectional area are provided in order to judge the functional capability at the different values of applied moments. Also scales of the maximum stresses and maximum strains which are encountered at the outer fibres of the convex side of the elbow are provided in order to indicate the state of the stress at the different values of applied moments.

The M-θ curves display the pipe softening as the applied rotation θ, increases past the instability point. The instability moment shown on the figures is defined on page 4 of this report.

On each curve, the ultimate moment values due to Gerber [2] is provided for comparison purposes. The curve M(Gerber)/B2 is included. The M-θ curve is consistently higher than M(Gerber)/B2, for all values of moment up to the instability moment. The ultimate moment due to Gerber is referred to herein as M_{ult}.

In Table 3, a summary of the percentage ovalization and percentage change in area is computed for a number of limit moments of the analyzed pipe sizes. The selection of those moments is based on definitions analogous to those of the ASME Code of the allowable design limits as per the rules of Appendix F for the design by analysis of piping components under Level D loading. Table F-1322.2-1 of the ASME Code is included in the Appendix to this report for convenience.

7.0 RESULTS (Cont'd)

The allowable moments are described as follows:

(1) $M(3S_m)/B2$:
$M(3S_m)$ is the moment that corresponds to an elastic stress distribution on the pipe cross section of a maximum value of $3S_m$. This moment is then divided by B_2 in order to account for the reduction in moment carrying capacity of elbows due to ovalization and stress concentrations as per Equation (9) of Section NB 3652.

(2) $0.7M_I$:
M_I is the instability moment, as defined in Appendix F, and is the value at which the moment carrying capacity of the pipe reduces, or at which the deformation increases without bound, i.e. the value at which the tangent to the $M-\theta$ curve is horizontal. The values of M_I are indicated in Figs. 3 to 7 of this report.

(3) $0.9\ M_{collapse}$:
$M_{collapse}$ as defined in Appendix F, is the moment at which the distortion is twice the value of the calculated initial departure from linearity, i.e. $M(2\varepsilon_y)$; the moment pertinent to maximum strain of twice ε_y. In this report a conservative evaluation of the collapse moment is based on a yield stress of $2.3S_m$. ε_y is obtained from $2.3S_m = S_o(\varepsilon_y)^n$. Notice that the overestimation of the limit moment results in a magnification of the functional capability parameters. See Appendix A for further discussion.

The values of $M_{collapse}$ are directly extracted from the finite elements results, for the calculated value of $2.0\ \varepsilon_y$ by using the strain scale of the $M-\theta$ curves. The 0.9 is inherent from the limit moment assumption ($S_y = 2.3\ Sm$).

7.0 RESULTS (Cont'd)

(4) 0.7 M_{ult}/B2:

M_{ult} as previously defined is the ultimate moment due to testing [Gerber, Ref. 2], which meets the code definition as an instability moment, and hence the factor 0.7. The division by B2 is meant to transform the test results on straight pipes into applicable values for elbows and other components.

From Table 3, it is evident that the employment of (0.7 M_{ult}/B2) as a limit moment is conservative since its values are in general, lower than the other limits (with the exception of the 1-1/2" diameter pipe, for which 0.7 M_{ult}/B2 practically agrees (slightly larger) with M(3S_m)/B2.

The employment of (0.7 M_{ult}/B2) as a functional capability criterion is in general, more appropriate than M(3S_m) since the former is obtained by plastic analyses which can better represent the plastic deformation phenomenon of elbows ovalization. However, for the specific pipe sizes considered, the highest ovalization pertaining to M(3S_m)/B2 equals 1.01% and the maximum area change for the same moment equals 0.13%, which are negligible. Note that prior to failure of the pipes, ovalization up to 45% and decrease in area as high as 35% are recorded (Figs. 3 to 9) but such moments are never approached if the requirements of ASME Codes are met. Typical percentage ovalization versus the bending moment in the elbow is shown on Fig. 11. As can be seen, ovalization is negligible for moments as close as 80% of M_I, after which it increases exponentially. Therefore, use of Level D stress limits is meaningful for these pipe sizes.

7.0 RESULTS (Cont'd)

The relationship between the instability moment predicted by the finite element plastic analysis and the instability moment drawn from the test results ($0.7M_I$ and $0.7M_{ult}/B2$) is demonstrated and is particularly accurate for the pipes of large t/R ratios.

The differences at smaller values of t/R (thinner pipes) is apparently due to the susceptability of thin pipes to local instability encountered in the tests due to the stress concentrations under the test loading apparatus rather than the instability moment collapse.

The primary stresses attributable to the bending of the elbow are accompanied by local secondary stresses that change from tension to compression across the thickness of the pipe wall and act in the circumferential direction of the pipe.

8.0 PIPING COMPONENTS OTHER THAN ELBOWS:

8.1 Functional Capability of Tee and Branch Connections.

8.1.1 Introduction

Presented here is a simplified engineering explanation aimed at proving that the functional capability of the tees and branch connections is well assured when the structural integrity Code requirements are satisfied.

The explanation provided is an analogy between branch connections and elbows so that the conclusions obtained from the plastic analysis of elbows can be utilized. It consequently follows that the discussion on functional capability is applicable only to tees and branch connections of the pipe sizes and thickness to radius ratios covered in the elbow analysis.

8.1.2 Tees versus Elbows

For an elbow, the decrease in cross sectional area under an applied bending moment is attributed to the ovalization of the circular section under the influence of the radially inward resultants of the tensile and compressive membrane forces in the concave and convex side of the elbow. This fact is schematically shown in Fig. 12. For a tee connection, while the decrease in cross sectional area is attributed to the same phenomenon, it is much more difficult to visualize and assess. This is due to three reasons:

8.0 PIPING COMPONENTS OTHER THAN ELBOWS: (Cont'd)

8.1 (Cont'd)

8.1.2 Tees versus Elbows (Cont'd)

First, the tee has three legs and as such, it could be subjected to three bending moments, the interaction of which is not immediately obvious. Second, unlike the elbow where stability can be achieved only if the bending moments at each leg are equal, for the tee there are infinite combinations of balanced bending moments acting on the three legs. Third, the distribution of stress and internal forces is more complicated in tees than in elbows.

The above three items must be addressed for any sound comparison of functional capability between tees and elbows.

8.1.3 Bending Moments on Tee Legs (the limiting case)

It will be shown here that as far as functional capability is concerned, all possible bending moment combinations on the three legs of the tees are bounded by a limiting case. This is the case where the tee is loaded by two equal bending moments on two perpendicular legs, (much as an elbow is loaded). To show that this is the limiting case, reference is made to Figure 13a which shows a tee loaded by a bending moment at each leg. The behavior of this tee can be thought of as resulting from the super-position of two loading conditions; one attempting to close the flow area, and other counteracting the first, attempting to open the flow area. This is schematically shown in Figure 13b. It is evident that the absence of the counteracting moment would result in the greatest area reduction.

8.0 PIPING COMPONENTS OTHER THAN ELBOWS: (Cont'd)

8.1 (Cont'd)

8.1.4 Stress patterns in the Tee

For the limiting loading case, namely, that where the tee is loaded similar to the elbow, the stress patterns are schematically represented in Figure 14. As can be seen from the stress distribution at section AB and section DC, the resultant forces acting at points B and D are similar to their counterparts (concave and convex sides) on the elbow. This will tend to close the diagonal cross section BD which does not represent a flow cross sectional area. The cross sections AB, CB, DC, however, will not be subject to ovalization. It is these latter sections that deliver the rated flow. Figure 14 shows how section DB may be ovalized while the perpendicular section (AB, BD & DC) shift more or less rigidly.

It can thus be concluded that the flow sections of tees and branch connections will ovalize less than elbows of the same properties. Since it was documented by elasto-plastic analysis that elbows undergo negligible area reduction under bending moments meeting Code requirements for structural integrity, the same holds true for tees and branch connections.

8.0 PIPING COMPONENTS OTHER THAN ELBOWS: (Cont'd)

8.2 Discussions on the Functional Capability of Straight Pipe and Reducers.

For the specific pipe sizes and schedules considered in this study, it was concluded that the functional capability parameters are acceptable for all elbows analyzed at the level D limits $0.7\ M_I$, $M(3S_m)/B_2$, $M_{collapse}$ and $0.7M_{ult}/B2$.
Notice that $M(3S_m)/B2$ is consistently bounded by $0.7\ M_I$ of elbows. Since straight pipes are more stable than elbows, for comparable loadings i.e., less prone to ovalization, it can be conservatively concluded that the functional capability will always be assured for straight pipes if level D limits are met.

Recognizing that B2 = 1.0 for reducers, that reducers are gradual transitions in straight piping, and that B2 has been demonstrated to be a meaningful parameter for functional capability, it is concluded that reducers are stable relative to elbows and not prone to gross deformations.

Therefore, elbows are considered to be the limiting case.

9.0 CONCLUSIONS

It has been demonstrated by finite element elastic-plastic analysis on elbows that meaningful functional capability limits can be derived based on the ultimate moments as defined by Gerber modified by the B_2 stress index for the piping component. Small deformations are assured if stresses less than 70% of the modified limit are maintained in the piping system. This criterion should be valid for any pipe size.

For the specific cases of relatively thick piping found in the Class 1 portions of pressurized water reactors and for Shearon Harris Nuclear Power Plant in particular, it is demonstrated that the small deformation limit defined above is bounded by a stress of $3.0S_m$ calculated by an elastic analysis. Therefore, for these specific cases, the ASME III Level D limits do in fact represent acceptable functional capability limits.

10.0 REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section III, Division 1, Pressure Vessels, 1977 Edition with Addenda up to and including Summer 1978, ASME, New York, NY.

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3. Rodabaugh, E.C., "Functional Capability Criteria for Essential Mark II Piping", Nuclear Energy Engineering Division, General Electric Company, San Jose, California, NEDO-21985, September 1978.

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7. McNeal Schwendler NASTRAN, Version 63 released August 12, 1983.

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SUMMARY OF CLASS 1 AUXILIARY PIPING TO BE EVALUATED FOR FUNCTIONAL CAPABILITY

TABLE I

	DESIGN BASIS EVENT							
	REACTOR COOLANT PIPE BREAK		SURGE LINE PIPE BREAK	RHR LINE(HL) PIPE BREAK	ACCUM LINE(CL) PIPE BREAK	MAIN STEAM PIPE BREAK	FEEDWATER PIPE BREAK	SAFE SHUTDOWN EARTHQUAKE
System/Class 1 Line	Line Attached to Broken Loop	Line Attached to Unbroken Loop				Line Attached to Any Loop		
Reactor Coolant System								
14" Surge Line	SI	SI	-	SI	SI	SI	E	E
4" Pressurizer Spray	SI/N (1)	SI	SI	SI	SI	SI	SI	SI
RCL Drain	N	SI	SI	SI	SI	SI	SI	SI
RTD	N	SI	SI	SI	SI	SI	SI	SI
RPV Vent	N	N	SI	SI	SI	SI	SI	SI
RPV Bottom Incore	SI	SI	SI	SI	SI	SI	SI	SI
6" Pressurizer PORV Inlet	SI	SI	SI	SI	SI	SI	SI	SI
6" Pressurizer SRV Inlet	SI	SI	SI	SI	SI	E	E	E
Chemical & Volume Control System								
3" Charging	SI/N (1)	SI	SI	SI	SI	SI	SI	SI
3" Letdown	N	SI	SI	SI	SI	SI	SI	SI
1-1/2" RCP Seal Water Inj	N	SI	SI	SI	SI	SI	SI	SI
3/4" RCP Bypass	N	SI	SI	SI	SI	SI	SI	SI
2" Boron Inj (C/L)	SI	E	E	E	E	E	E	E
Residual Heat Removal System								
12" RHR Suction	SI	SI	SI	-	SI	SI	SI	SI
Safety Injection System								
12" Accumulator Inj	SI	E	E	E	E	SI	SI	E
6" SIS to Cold Leg	SI	E	E	E	E	E	SI	E
6" SIS to Hot Leg	SI	E	E	E	E	SI	SI	E

TABLE - I
NOTES AND DEFINITIONS

E - Essential line - required to function and maintain its pressure boundary.

SI - non-essential line (structural integrity line) - required to maintain its pressure boundary only.

N - not required to function or maintain its pressure boundary.

(1) - SI - for hot leg break
N - for cold leg and crossover leg break

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SHEARON HARRIS NUCLEAR POWER PLANT
FUNCTIONAL CAPABILITY OF ASME CLASS 1
AUXILIARY PIPING SYSTEMS

TABLE II
PROPERTIES OF ANALYZED PIPE SIZES

NOMINAL PIPE SIZE (IN.)	PIPE SCHEDULE	OUTSIDE DIAM. (IN.)	INSIDE DIAM. (IN.)	WALL THICKNESS (IN.)	INSIDE AREA (IN.^{2})	MOMENT OF INTERTIA (IN.^{4})	SECTION MODULUS (IN.^{3})	t/R THICKNESS NOM. RAD.	B2	SHAPE FACTOR
1-1/2	160	1.90	1.338	0.281	1.406	0.483	0.508	0.3471	1.4978	1.46510
3	160	3.50	2.626	0.437	5.42	5.03	2.876	0.2809	1.6416	1.4355
6	160	6.625	5.189	0.718	21.15	59.0	17.81	0.2434	1.7864	1.4141
12	140	12.75	10.50	1.125	86.6	701.	109.9	0.193	2.0573	1.3878
14	160	14.0	11.188	1.406	98.3	1017.	159.6	0.2233	1.7802	1.40377

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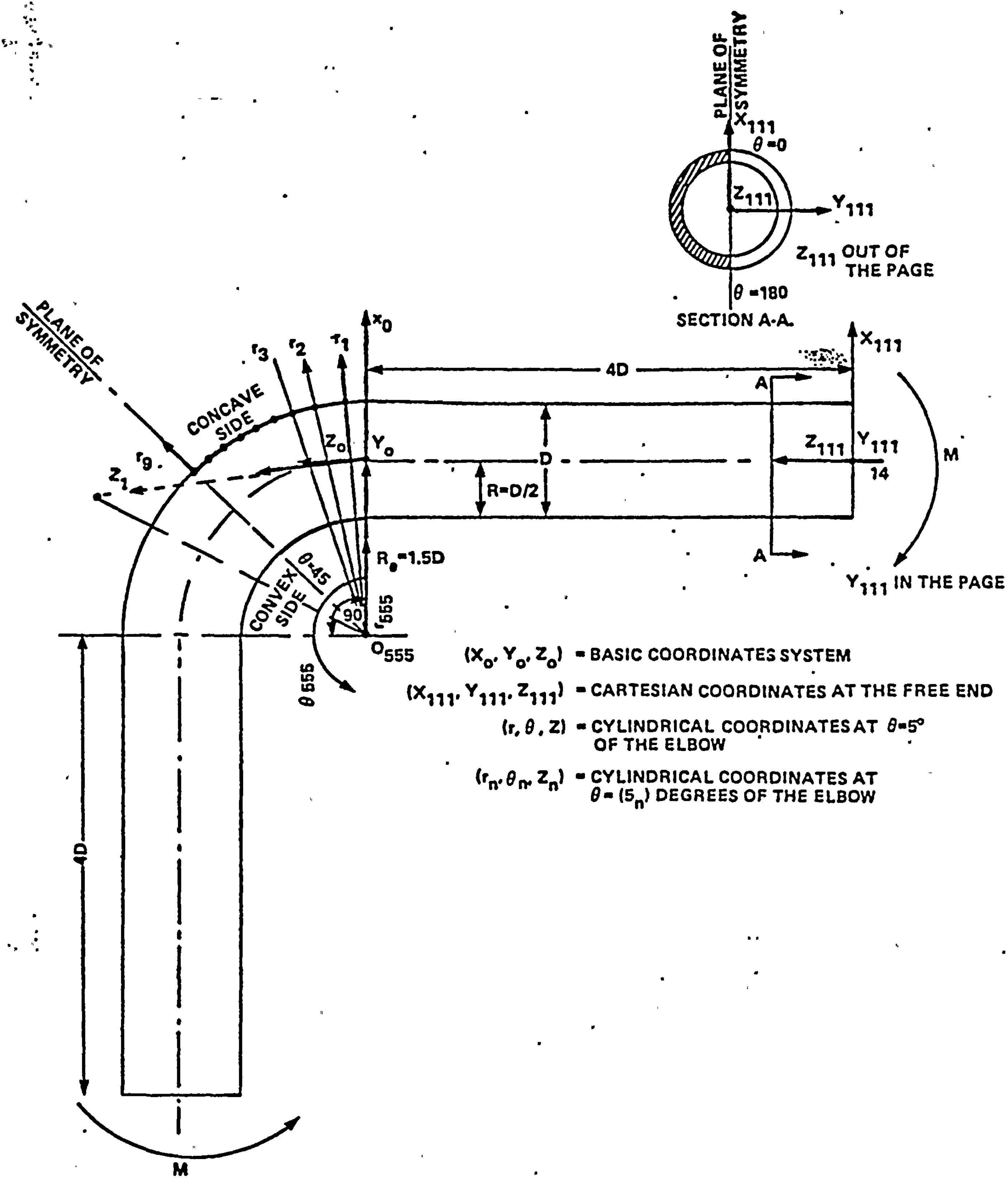
FUNCTIONAL CAPABILITY OF ASME CLASS 1
AUXILIARY PIPING SYSTEMS

TABLE III
OVALIZATION AND PERCENT CHANGE IN AREA FOR ALTERNATE CODE DEFINITIONS OF COMPONENT LIMIT MOMENTS

APPROACH		ELASTIC	PLASTIC (FINITE ELEMENT)		MODIFIED TEST RESULTS
LINE SIZE & ELBOW PARAMETERS	COMPARISON PARAMETERS	$M(3S_m)/B2$ 10^6 in-lb	$0.7M_I$ 10^6 in-lb	$0.9M_{collapse}$ ($S_y = 2.3S_m$) 10^6 in-lb	$0.7\ M_{ult}/B2$ 10^6 in-lb
1-1/2"	Moment	0.0165	0.017	0.019	0.0169
$B_2 = 1.4978$	Ovalization	0.81%	0.87%	1.88%	0.87%
$t/R = 0.3471$	Area Change	0.13%	0.157%	0.40%	0.157%
3"	Moment	0.0851	0.095	0.106	0.0833
$B_2 = 1.6416$	Ovalization	0.93%	1.41%	2.48%	0.925%
$t/R = 0.2809$	Area Change	0.13%	.21%	0.43%	0.12%
6"	Moment	0.485	0.541	0.623	0.454
$B_2 = 1.7864$	Ovalization	0.85%	1.45%	2.87%	0.613%
$t/R = 0.2434$	Area Change	0.07%	0.17%	0.41%	0.037%
12"	Moment	2.676	2.99	3.47	2.49
$B_2 = 2.0573$	Ovalization	1.01%	1.71%	3.74%	0.698%
$t/R = 0.193$	Area Change	0.048%	0.12%	0.43%	0.032%
14"	Moment	4.357	5.18	5.94	3.997
$B_2 = 1.7802$	Ovalization	0.64%	1.61%	2.84%	0.405%
$t/R = 0.2233$	Area Change	0.04%	0.16%	0.40%	0.030%

FIG. 1-A
SCHEMATIC REPRESENTATION OF THE FINITE ELEMENT MODELED ELBOW



(X_0, Y_0, Z_0) = BASIC COORDINATES SYSTEM

$(X_{111}, Y_{111}, Z_{111})$ = CARTESIAN COORDINATES AT THE FREE END

(r, θ, Z) = CYLINDRICAL COORDINATES AT $\theta = 5°$ OF THE ELBOW

(r_n, θ_n, Z_n) = CYLINDRICAL COORDINATES AT $\theta = (5_n)$ DEGREES OF THE ELBOW

FIGURE 1b
PLOT OF THE ELBOW FINITE ELEMENT MODEL

6" ϕ ELBOW

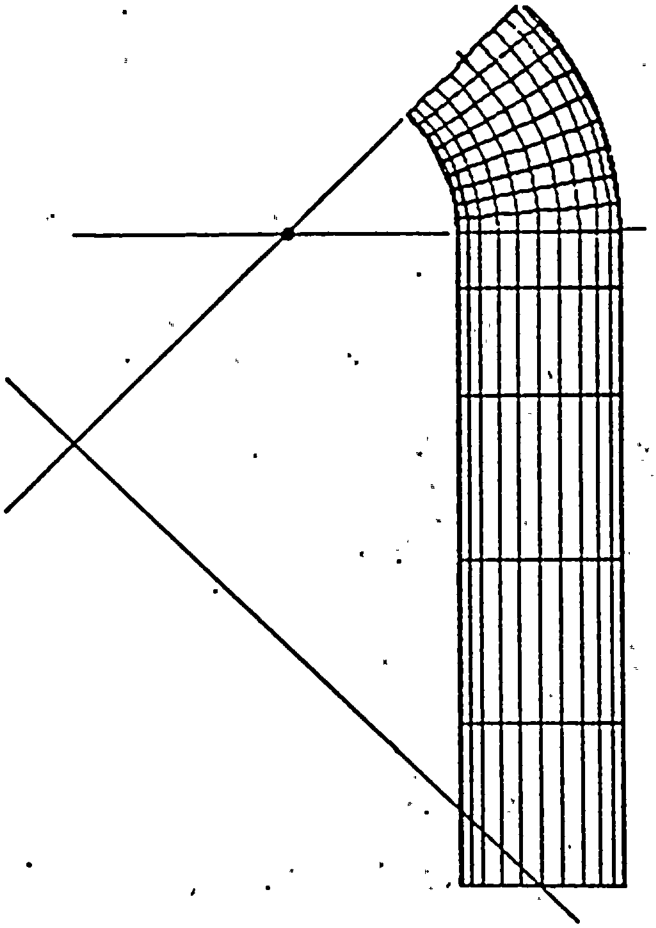


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FIGURE 1c
PLOT OF THE ELBOW FINITE
ELEMENT MODEL

6" ϕ ELBOW

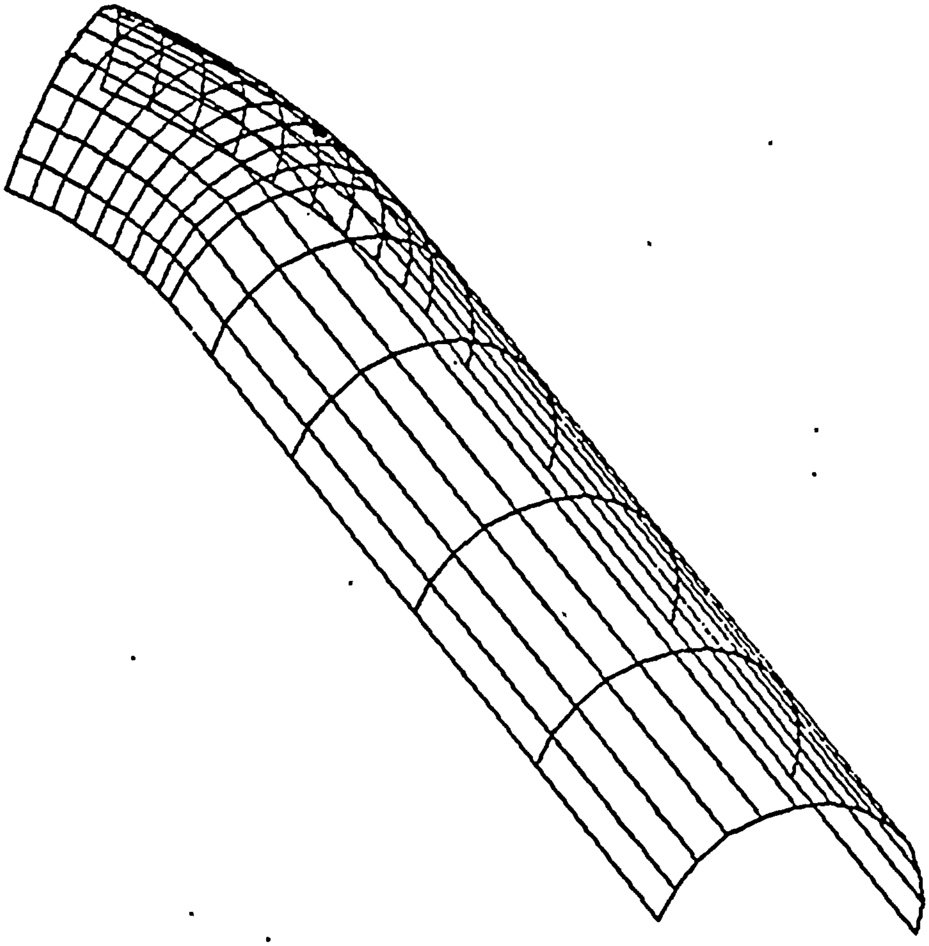

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FIGURE 2
STRESS STRAIN CURVE OF THE
MODELED ELBOW MATERIAL

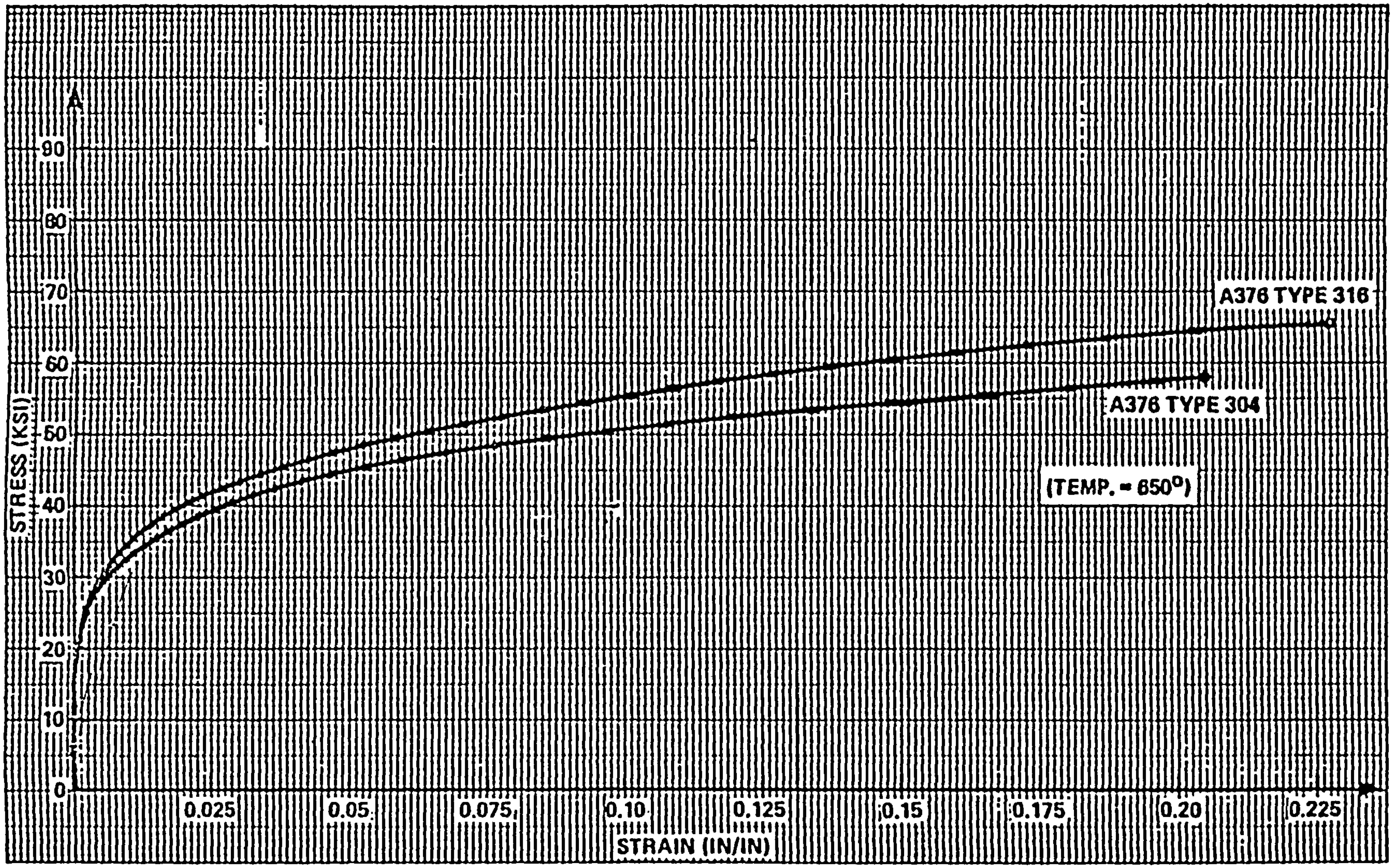

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FIG. 3
(M-θ) FINITE ELEMENTS RESULTS OF THE 1½" ELBOW

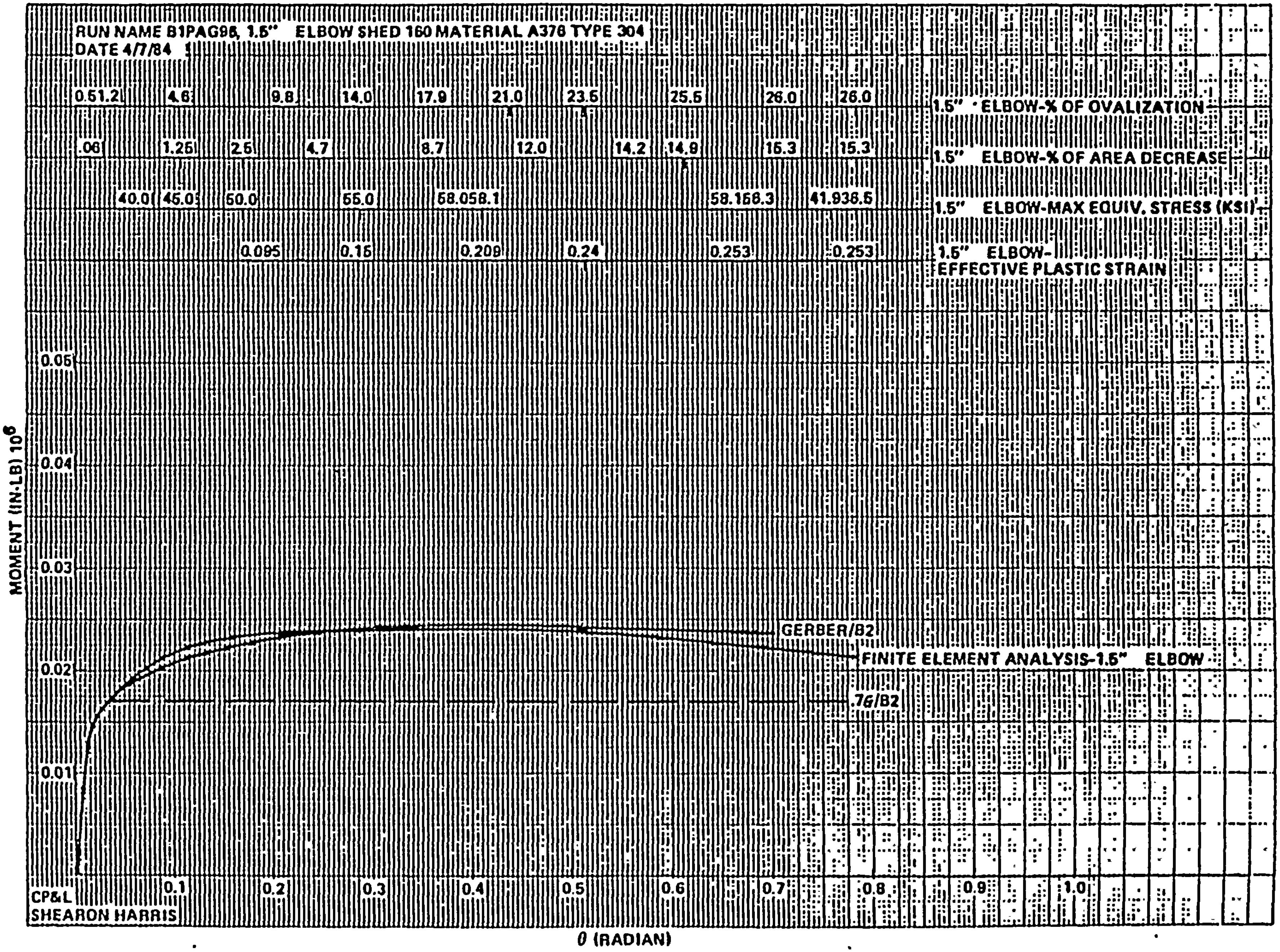
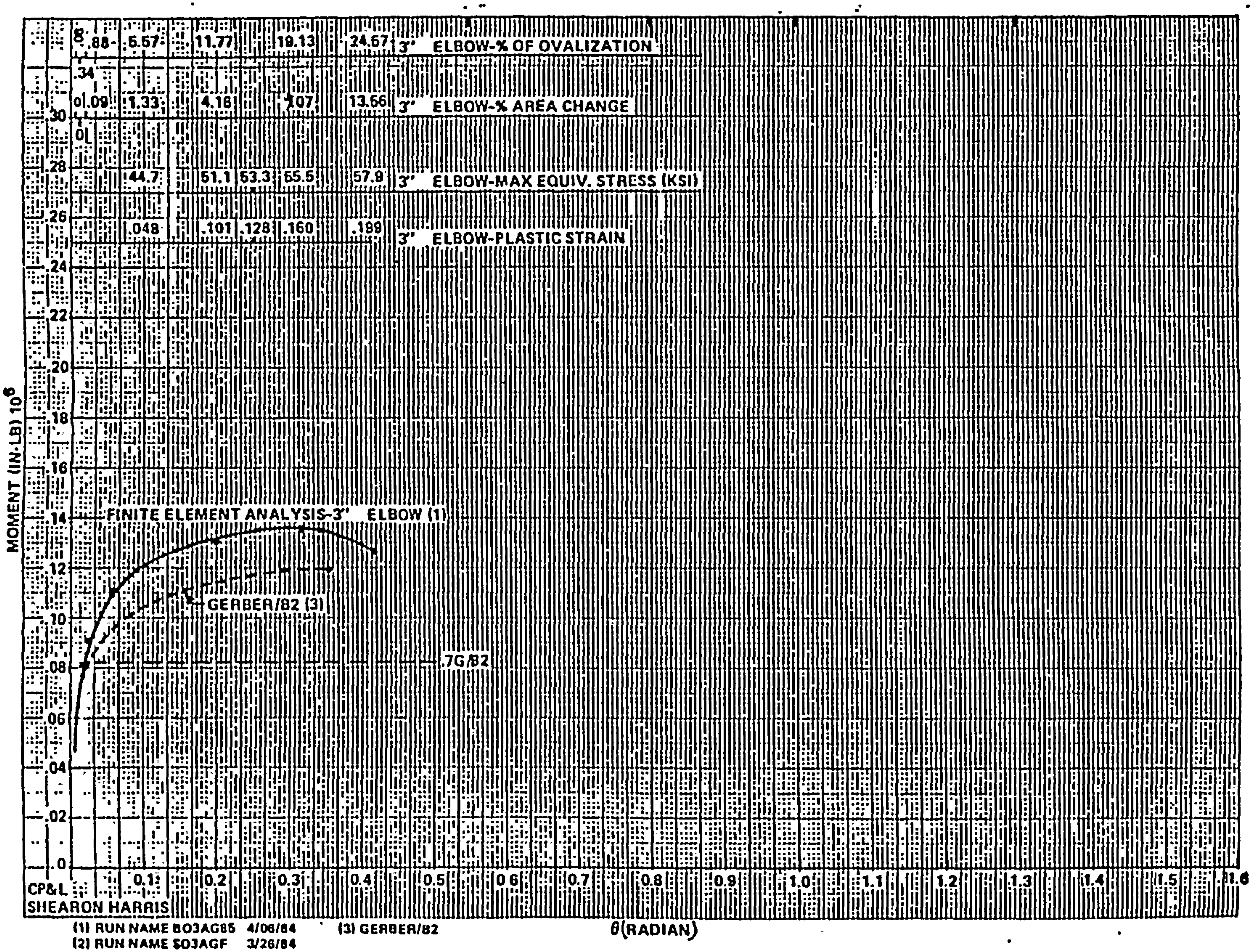
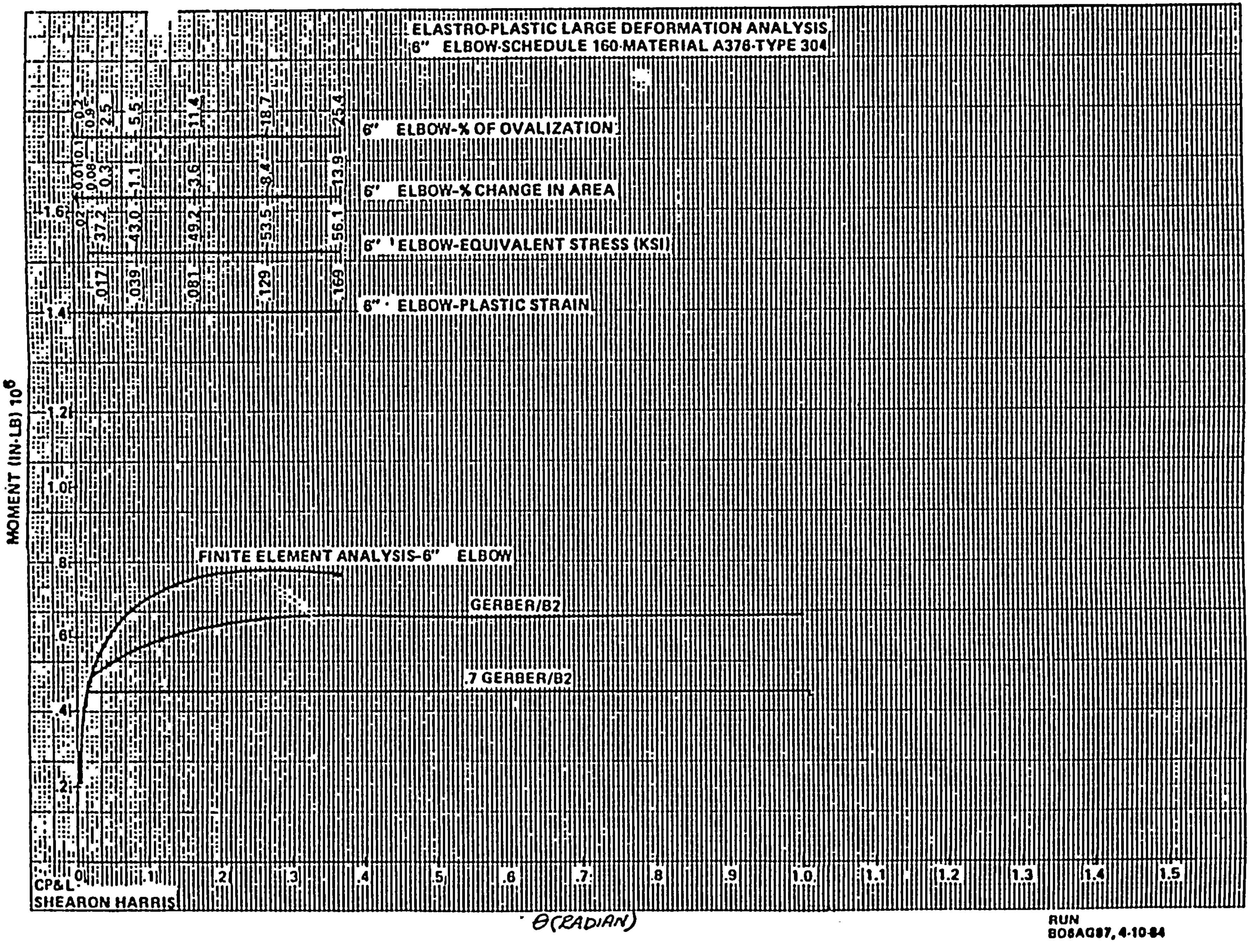


FIG. 4
(M-θ) FINITE ELEMENTS RESULTS OF THE 3" ELBOW



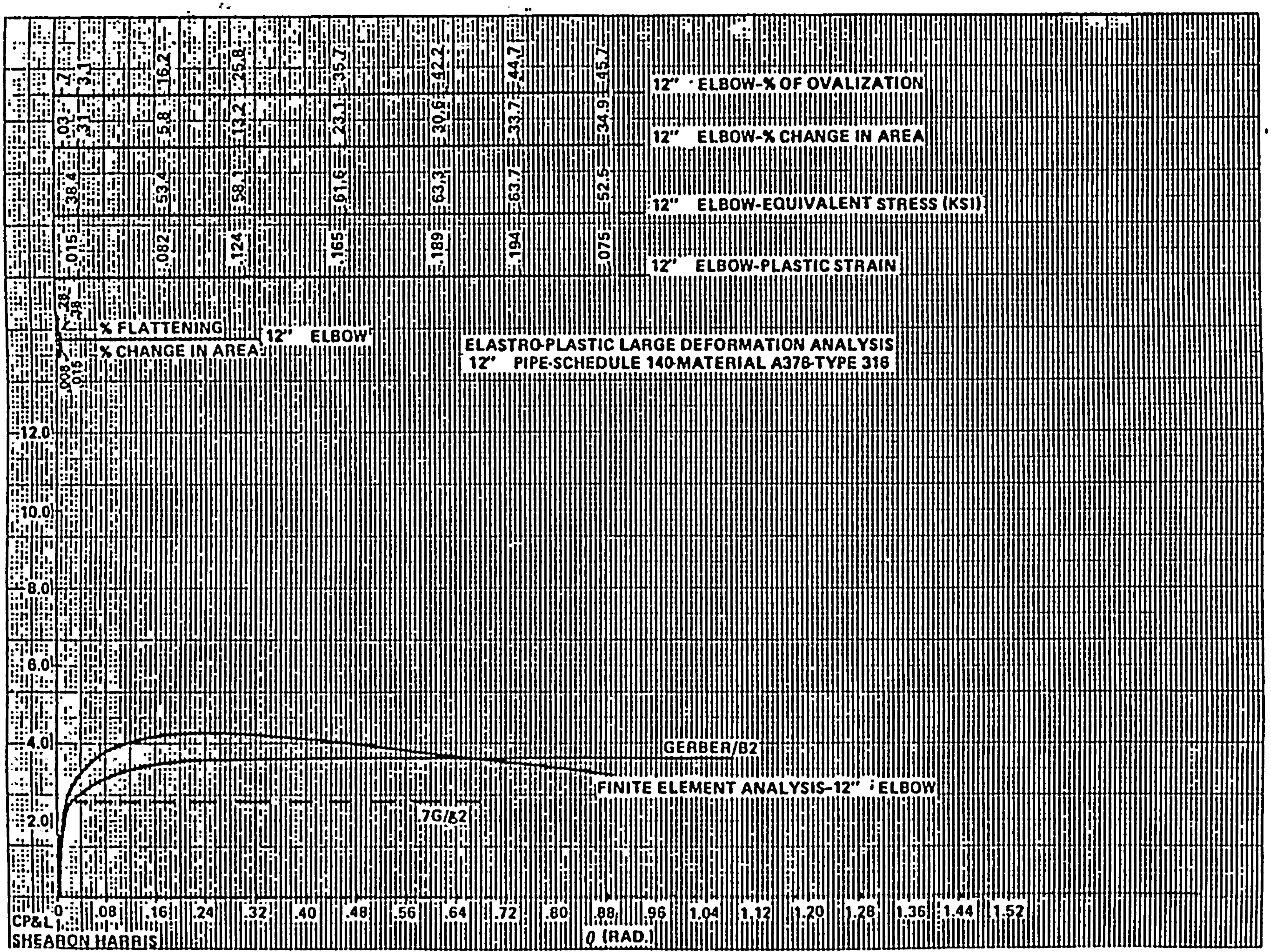
(1) RUN NAME BO3AG85 4/06/84 (3) GERBER/82
(2) RUN NAME SO3AGF 3/26/84

FIG. 5
(M-θ) FINITE ELEMENTS RESULTS OF THE 6" ELBOW



RUN
B06AG87, 4-10-84

FIG. 6
(M-θ) FINITE ELEMENTS RESULTS OF THE 12" ELBOW



RUN NAME
E12 AG 83, 4-6-84
SOZAGFV 3-30-84

FIG. 7
(M-θ) FINITE ELEMENTS RESULTS OF THE 14" ELBOW

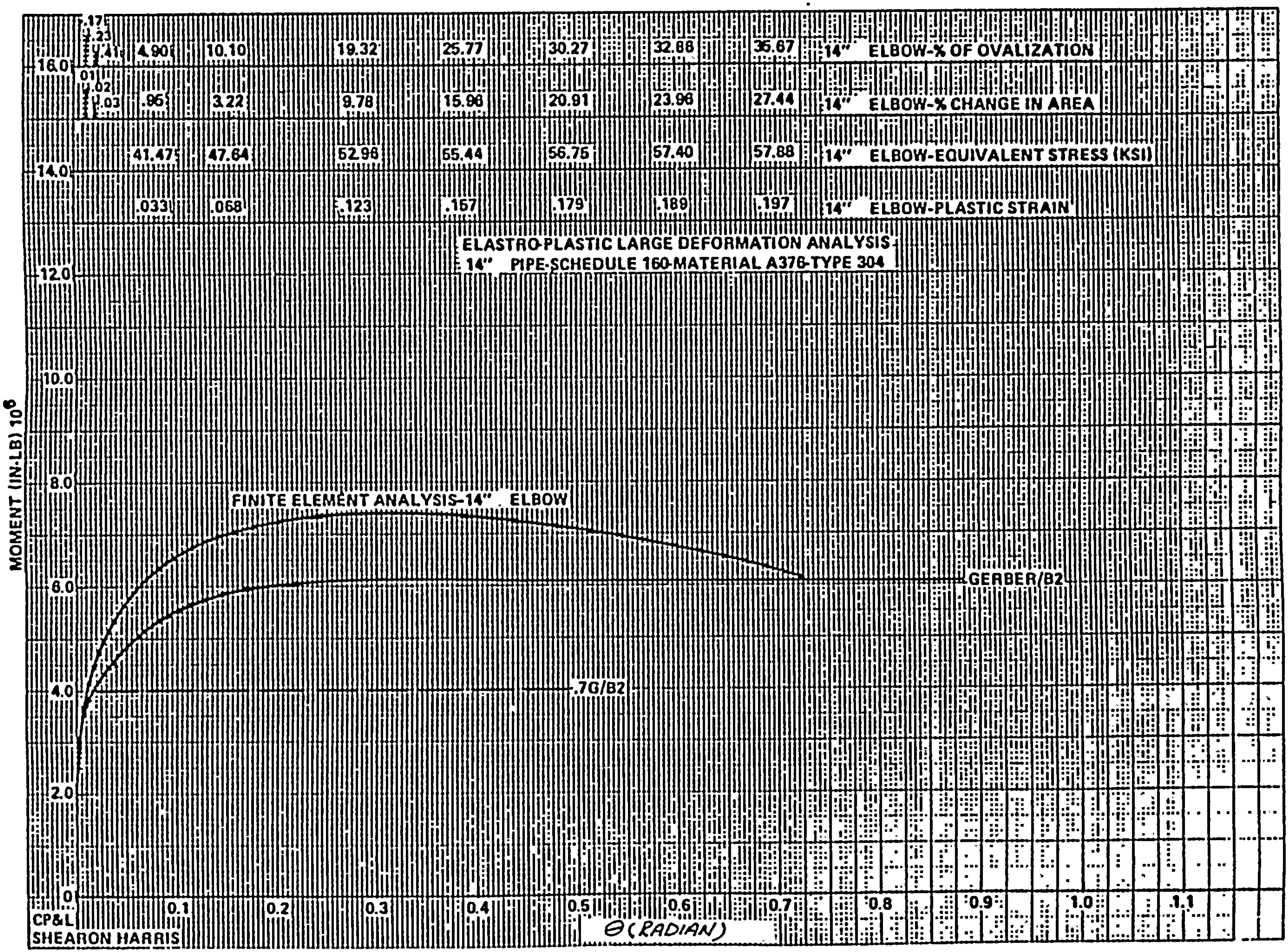
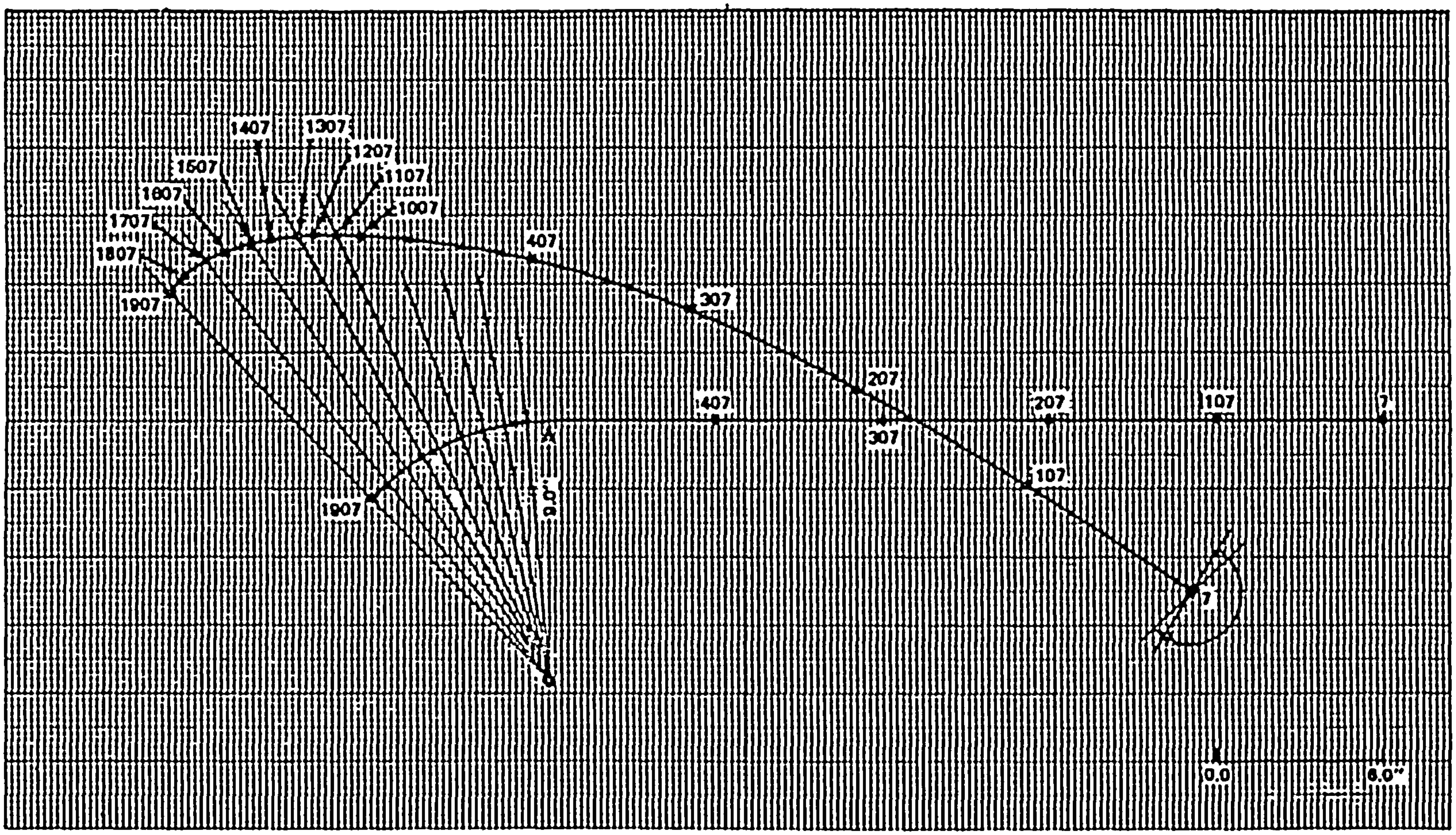


FIGURE 8
DEFORMATION SHAPE OF THE MODELED PIPE UNDER THE APPLIED MOMENT

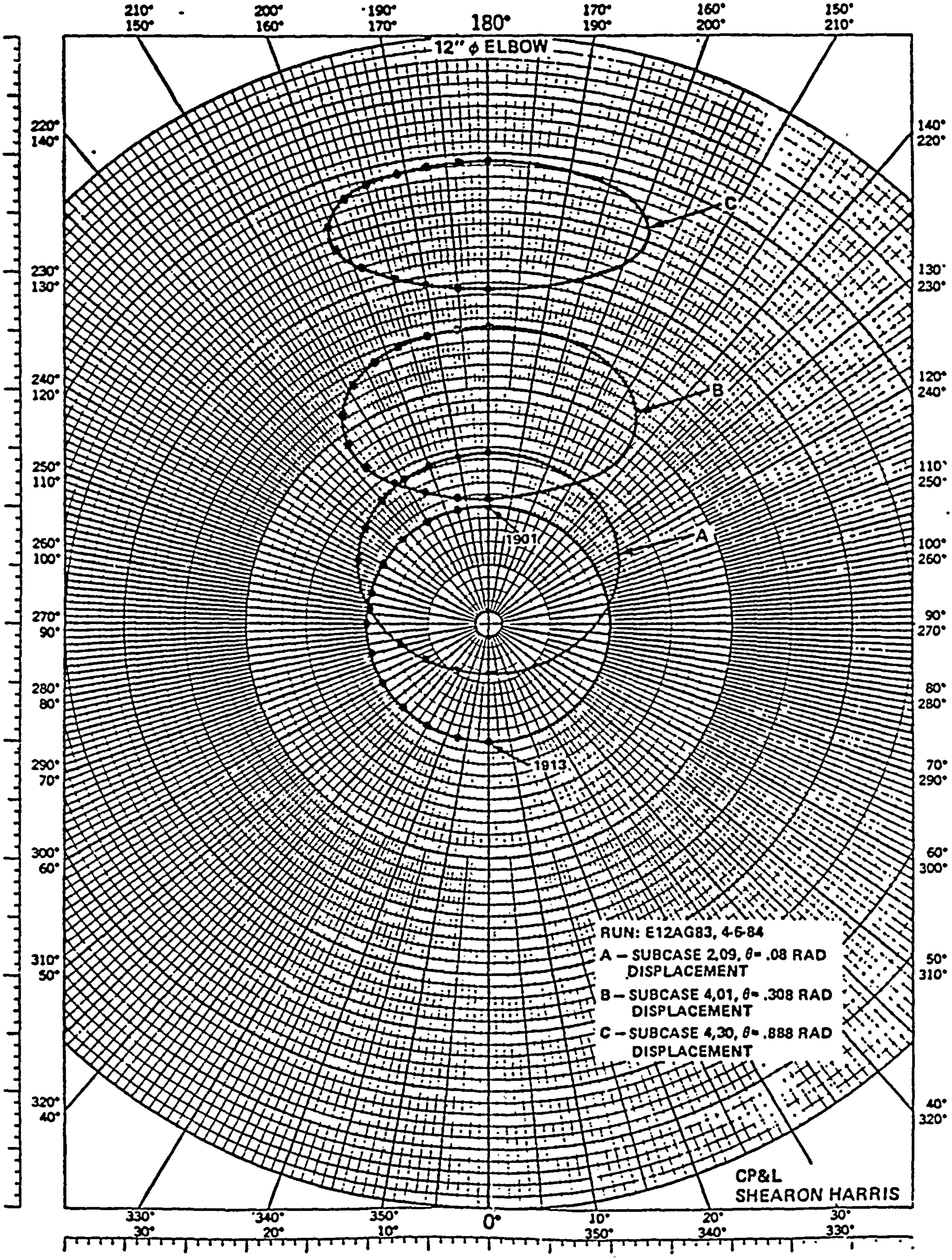
6" ELBOW SCH 160

SUBCASE 4, 5



SCALE 1:6 IS USED FOR BOTH PIPE LENGTH AND ITS DEFORMATIONS.

FIGURE 9
TYPICAL PROGRESSIVE DEFORMATION OF THE ELBOW'S CROSS SECTION OBTAINED BY THE FINITE ELEMENT METHOD



RUN: E12AG83, 4-6-84
A – SUBCASE 2,09, θ= .08 RAD DISPLACEMENT
B – SUBCASE 4,01, θ= .308 RAD DISPLACEMENT
C – SUBCASE 4,30, θ= .888 RAD DISPLACEMENT

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FIGURE 10
PROGRESSIVE ELASTO-PLASTIC STRESS DISTRIBUTION OBTAINED FROM THE FINITE ELEMENTS RESULTS

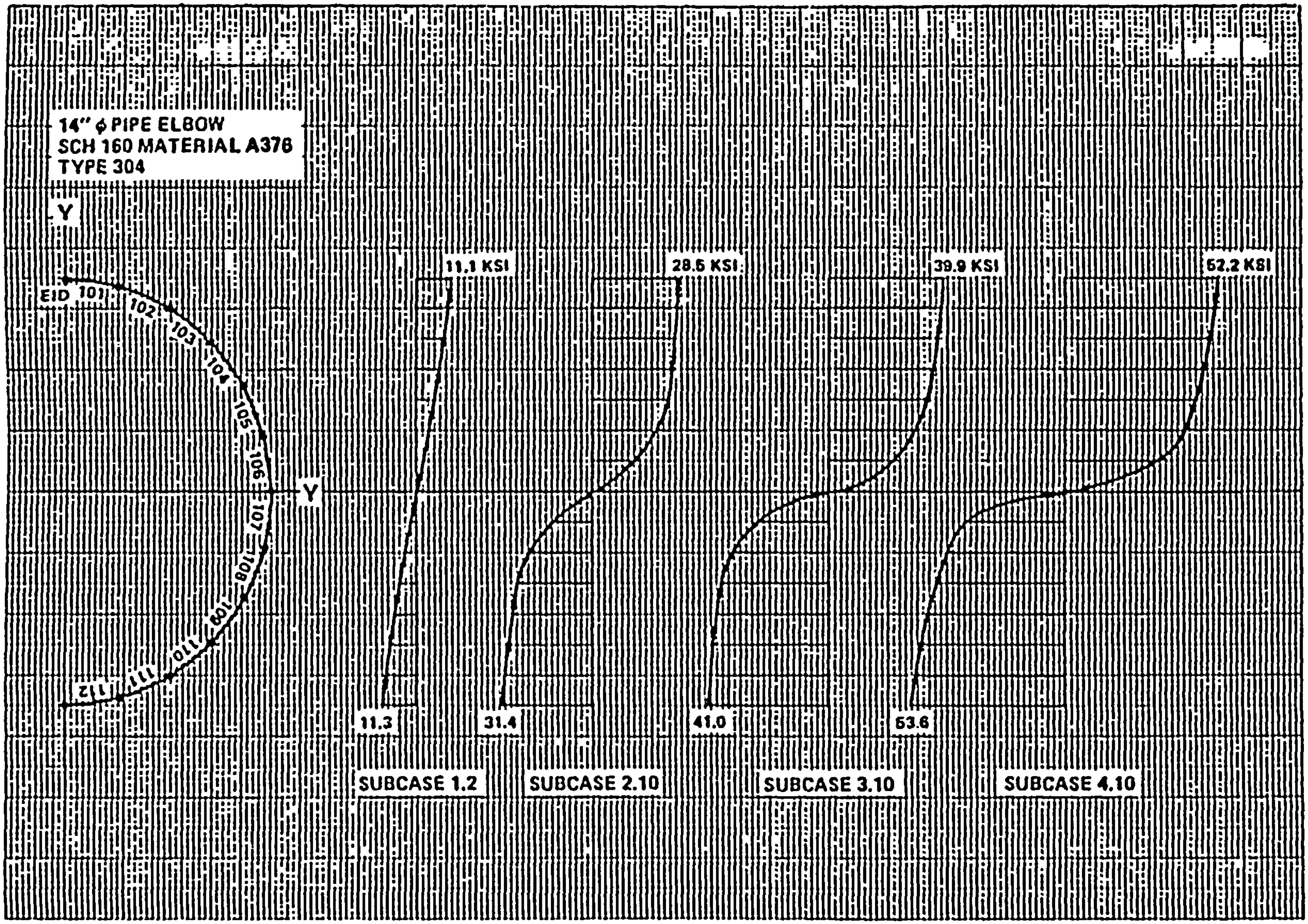

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FIGURE 11
PERCENTAGE FLATTENING VERSUS BENDING MOMENT

ELASTO -PLASTIC LARGE DEFORMATION ANALYSIS

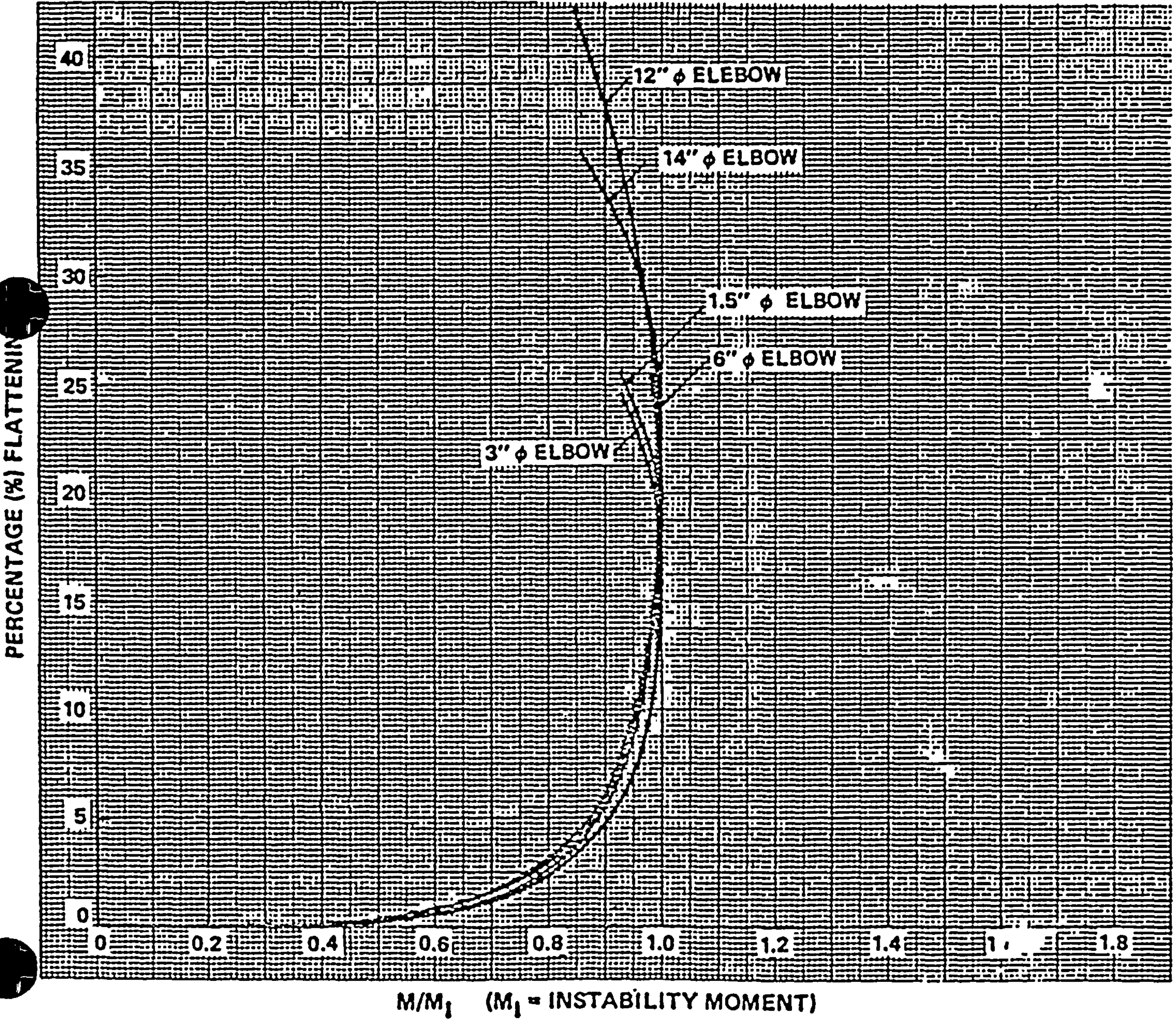

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FIGURE 12
REPRESENTATION OF DECREASE IN CROSS SECTIONAL AREA OF AN ELBOW UNDER APPLIED BENDING MOMENTS

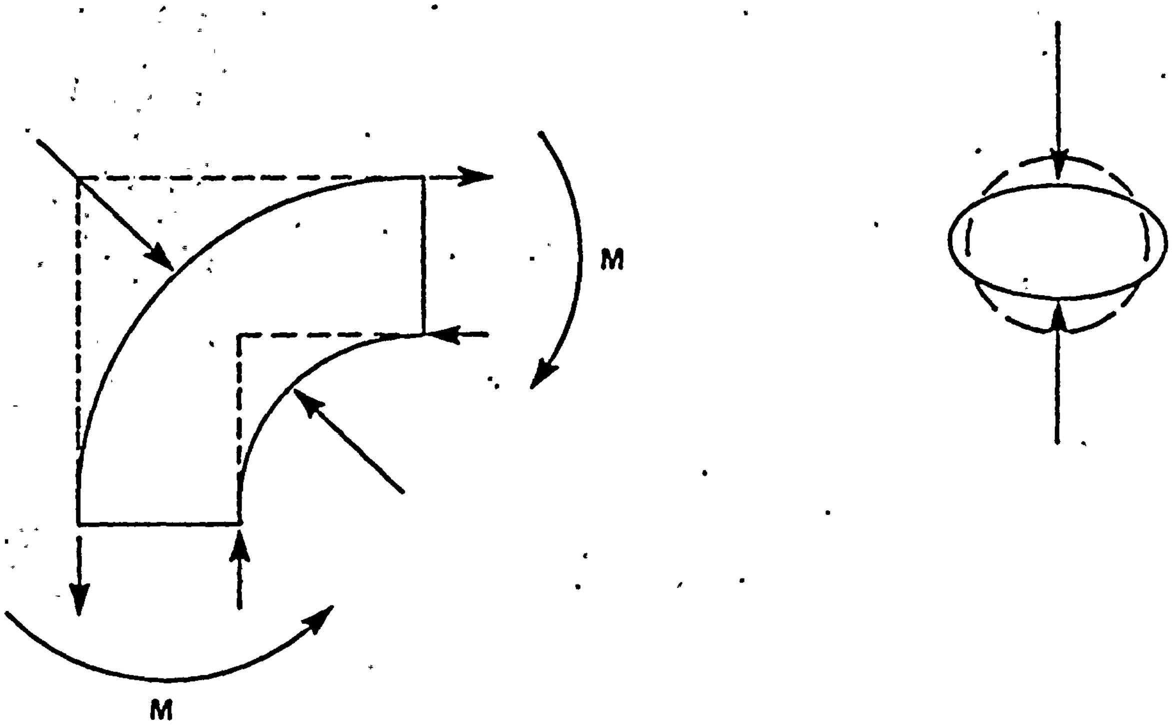
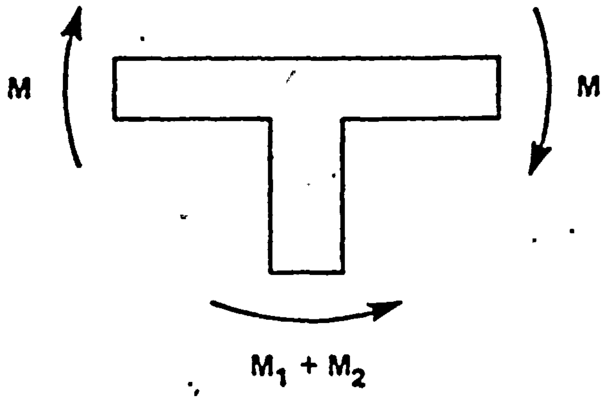


FIGURE 13
TEE SECTION UNDER GENERAL BENDING MOMENTS

13-A



13-B

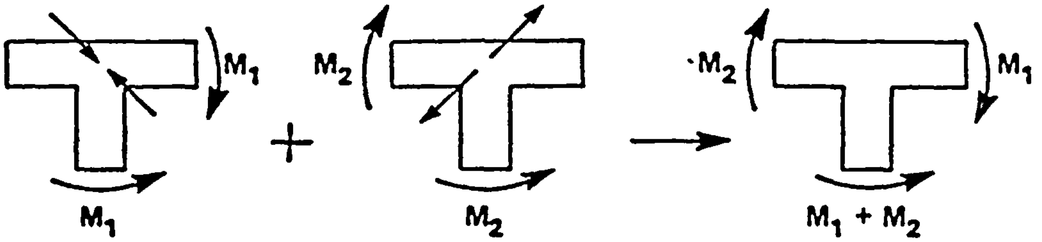
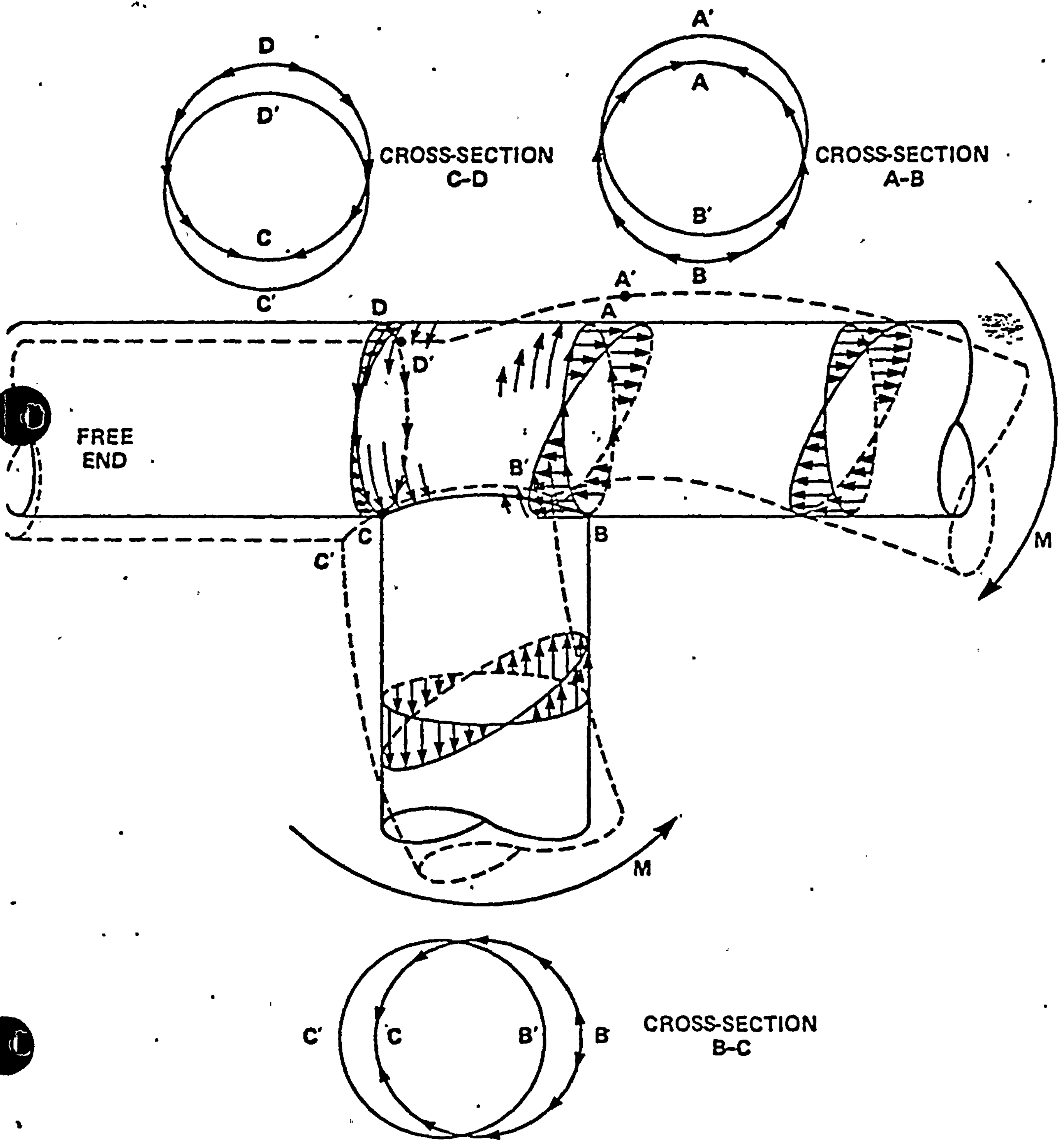


FIGURE 14
STRESS PATTERNS IN TEES UNDER LIMITING
BENDING MOMENT CASE



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SHEARON HARRIS NUCLEAR POWER PLANT
FUNCTIONAL CAPABILITY OF ASME CLASS 1
AUXILIARY PIPING SYSTEMS

APPENDIX A

SENSITIVITY STUDIES

INTRODUCTION

In this report, the strain power law is used to describe the material stress-strain data in the plastic zone; whereas the elastic properities are defined by using Young's modulus of elasticity E as given in the code, see Figure 2. The intersect point which is the proportional limit S_p equals 20.4 ksi for the A-376-304 material and equals 20.5 ksi for the A-376-316 material. Accordingly, the yield stress S_y defined by the 0.2% strain offset equals 26.4 ksi for A-376-304 and 27.08 for A-376-316. The code values for S_y of the two materials at 650°F equal 17.9 ksi and 18.5 ksi respectively. The quoted values of S_p and S_y clearly indicate that the strain power law inherently overestimates the stress values in the small stress zone. However, in the report, the stress-strain curves of Figure 2 are not modified to reflect the code values of S_y, since it is believed that the results of plastic analysis are independent of the stress-strain data in the small-strain zone.

Sensitivity studies are conducted, however, to document the above concept and to prove beyond any doubt, that the functional capability parameters (ovalization and change in area) remain acceptable when using the material presentation that meets the code value of S_y which is referred to hereafter as Material (3). It has been demonstrated that the instability moment M_I is insensitive to the changes in S_p and S_y, yet it depends mostly on the ultimate stress value S_u and on the shape of the stress-strain curve at large, regardless of the details of it in the small-strain zone.

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SHEARON HARRIS NUCLEAR POWER PLANT
FUNCTIONAL CAPABILITY OF ASME CLASS 1
AUXILIARY PIPING SYSTEMS

APPENDIX A

INTRODUCTION: (Cont'd)

For the "new material" (3) that meet the code value of S_y, the functional capability parameters remain to be very small and practically negligible, at the code limit moments of $M(3S_m)$ and $0.7\ M_I$.

Moreover, the functional capability parameters at the collapse moment M_c as defined by Appendix F of the ASME Code and according to the values of Paragraph II-1430 proved to be of even smaller values for the "new material (3)".

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SHEARON HARRIS NUCLEAR POWER PLANT
FUNCTIONAL CAPABILITY OF ASME CLASS 1
AUXILIARY PIPING SYSTEMS

APPENDIX A

ANALYSIS AND RESULTS

Figure A.1 illustrates 3 material representation of the SS A 376-304 material as employed in this sensitivity study:

A summary of the 3 representatives is given as follows:

Material Representation Number	Description	E 10^6psi	Proportional Unit S_p Ksi	Yield Stress S_y Ksi	Plastic Properties
(1)	Material used in Report (Fig 2)	25.5	20.4	26.4	Strain power law as shown on Fig 2
(2)	Extremely softened material in the vicinity of Sy	25.5	4.0	14.0	"
(3)	Code value of S_y is best fit	25.5	12.221	17.9	"

The 3 materials are employed in the Finite element analysis of the 6" elbow and the performance curves ($M-\theta$) are determined. Figure A.2 represents the ($M-\theta$) curve of the Material (2). and Figure A.3 represents the ($M-\theta$) curve of the Material (3). By comparing the aforementioned figures with their Material (1) counterpart (Fig 5), it becomes apparent that M_I has hardly changed from one material to the other. In fact 2%, and 1/2% deviation of M_I are recorded for material (2) and (3) respectively w.r.t M_I of Material (1).

The results of the 3 material representations are augmented in Figure A-4, which displays the moments as functions of percentage flattening (ovalization). A scale of the % change in area is also included.

APPENDIX A

ANALYSIS AND RESULTS (Cont'd)

Figure A-4 proves that the % flattening vary but only slightly (1%) from one material to the other and clearly indicates that the flattening at the $M(3S_m)/B_2$ and 0.7 M_I moments are still negligible.

The comparison parameters of the 3 material representation are presented in table A-1.

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SHEARON HARRIS NUCLEAR POWER PLANT
FUNCTIONAL CAPABILITY OF ASME CLASS 1
AUXILIARY PIPING SYSTEMS

APPENDIX A

COLLAPSE MOMENT Mc

The collapse moment $M_{collapse}$ definition used in this report represents an upper bound that is analogous to the code definition. The collapse moment M_c is introduced here for comparison purposes. M_c is defined in accordance with Appendix F and by using the rules of II-1430. The values of M_c along with the illustration of the code interpretation of II-1430 are presented in figure A-5. The flattening and percent change in area at the M_c values of the 3 material representations are given on figure 5. It is then concluded that the functional capability parameters evaluated at M_c are much smaller for the softer materials since smaller values of M_c are obtained for the latter.

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SHEARON HARRIS NUCLEAR POWER PLANT
FUNCTIONAL CAPABILITY OF ASME CLASS 1
AUXILIARY PIPING SYSTEMS

APPENDIX A

BACK-UP STUDIES:

M(3Sm) versus Mult:

Computations of the elastic moment that correspond to a maximum stress of $3S_m$ of a straight pipe, i.e. $M(3S_m)$, for different pipe sizes that vary from 1-1/2" to 14", and for its various pipe schedules, i.e. various t/R_o ratios, were conducted. Similar computations of the ultimate moment M_{ult} as defined by Gerber (2) were also undertaken. The values of S_m and S_u are taken at a 650°F temperature.

The ratio of 0.7 $M_{ult}/B2$ versus $M(3S_m)/B2$ for elbows are plotted versus t/R_o. As expected, the ratios of moments as obtained from the vast range of sizes and schedules, all fell on the same curve. Illustrated in Figure A-6 is the mentioned curve, which can be thought of as $0.7S_u/3S_m$ times "Gerber's shape function". The shape function is also plotted versus t/R_o for the variety of the pipe sizes. In order to bring the comparison in perspective, the ratio of $0.7S_u/3S_m$ is used as a multiplier to the shape function and the resulting curve is included on Figure A-6. A cut-off point of t/R_o = .26 exists, where 0.7 M_{ult} exceeds $M(3S_m)$ for higher values of t/R_o and visa-versa.

The shape factor (function) is defined as the ratio of the limit plastic moment with uniform stress distribution versus the elastic moment of the sand maximum stress value. In other words, the ratio of the plastic section modulus to the elastic section modulus.

It is clear from Figure A-6 that the "shape factor" inherent in Gerber's definition of M_{ult} is bounded by the conventional shape factor and that both functions exhibit similar trends.

APPENDIX A

BACK-UP STUDIES: (Cont'd)

M(3Sm) versus Mult: (Cont'd)

Notice that the range of t/Ro of the pipes considered in this report is from 0.18 to 0.296 (quoted in the report are values of t/R from .223 to .347 for which R is the nominal radius).

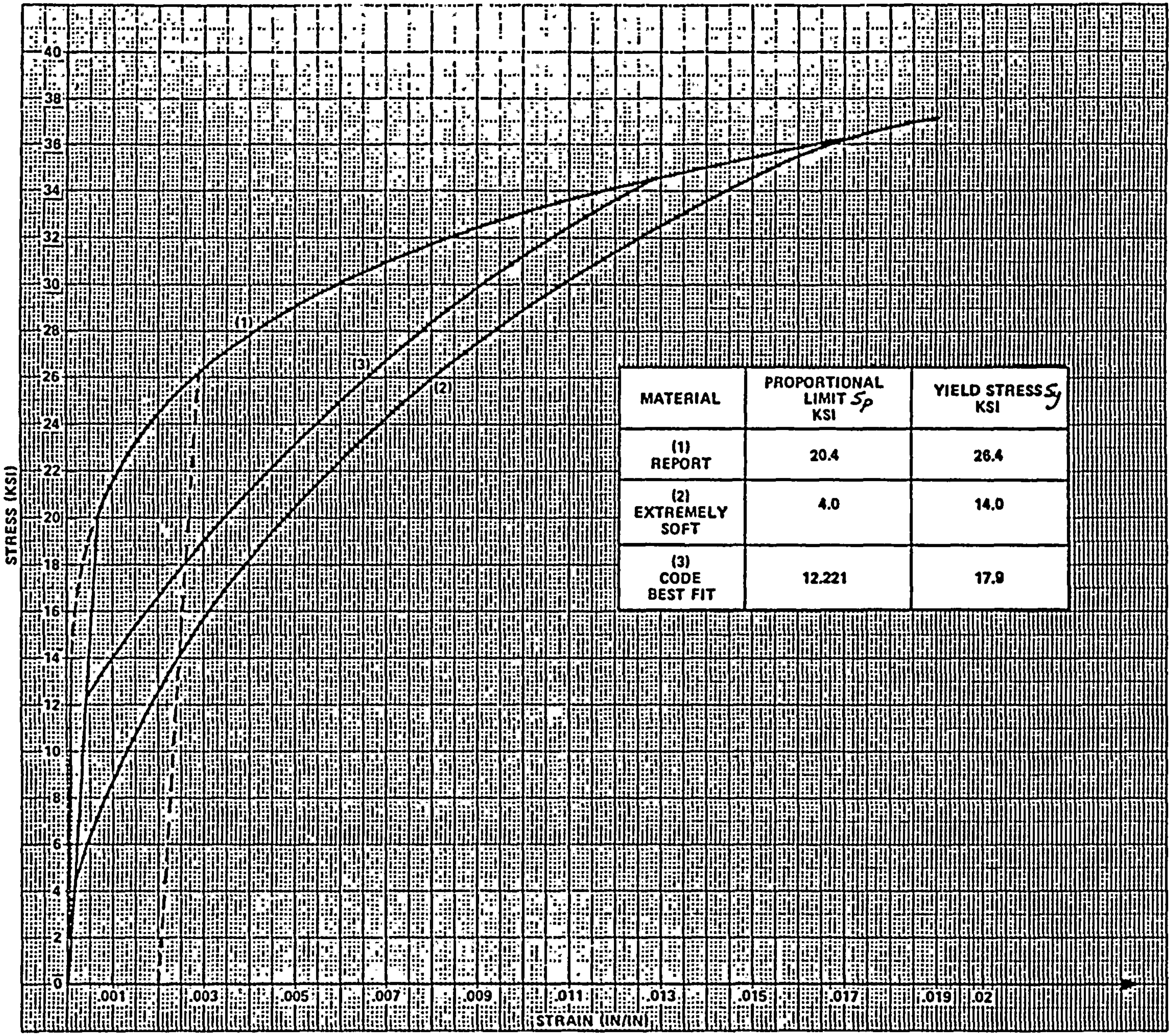
The highest ratio of $M(3S_m)/0.7\ M_{ult}$ for this range of piping equals 1.09. For the 1-1/2" pipe (t/Ro = 0.296), the value of $0.7\ M_{ult}$ slightly exceeds $M(3S_m)$.

CAROLINA POWER AND LIGHT COMPANY
SHEARON HARRIS NUCLEAR POWER PLANT
FUNCTIONAL CAPABILITY OF ASME CLASS 1 AUXILIARY PIPING SYSTEMS

APPENDIX A

LIST OF ILLUSTRATIONS

FIGURE A-1
A-376-304 MATE[illegible] REPRESENTATION IN THE SMALL-STRAIN Z[illegible] FOR SENSITIVITY STUDIES



MATERIAL	PROPORTIONAL LIMIT S_p KSI	YIELD STRESS S_y KSI
(1) REPORT	20.4	26.4
(2) EXTREMELY SOFT	4.0	14.0
(3) CODE BEST FIT	12.221	17.9

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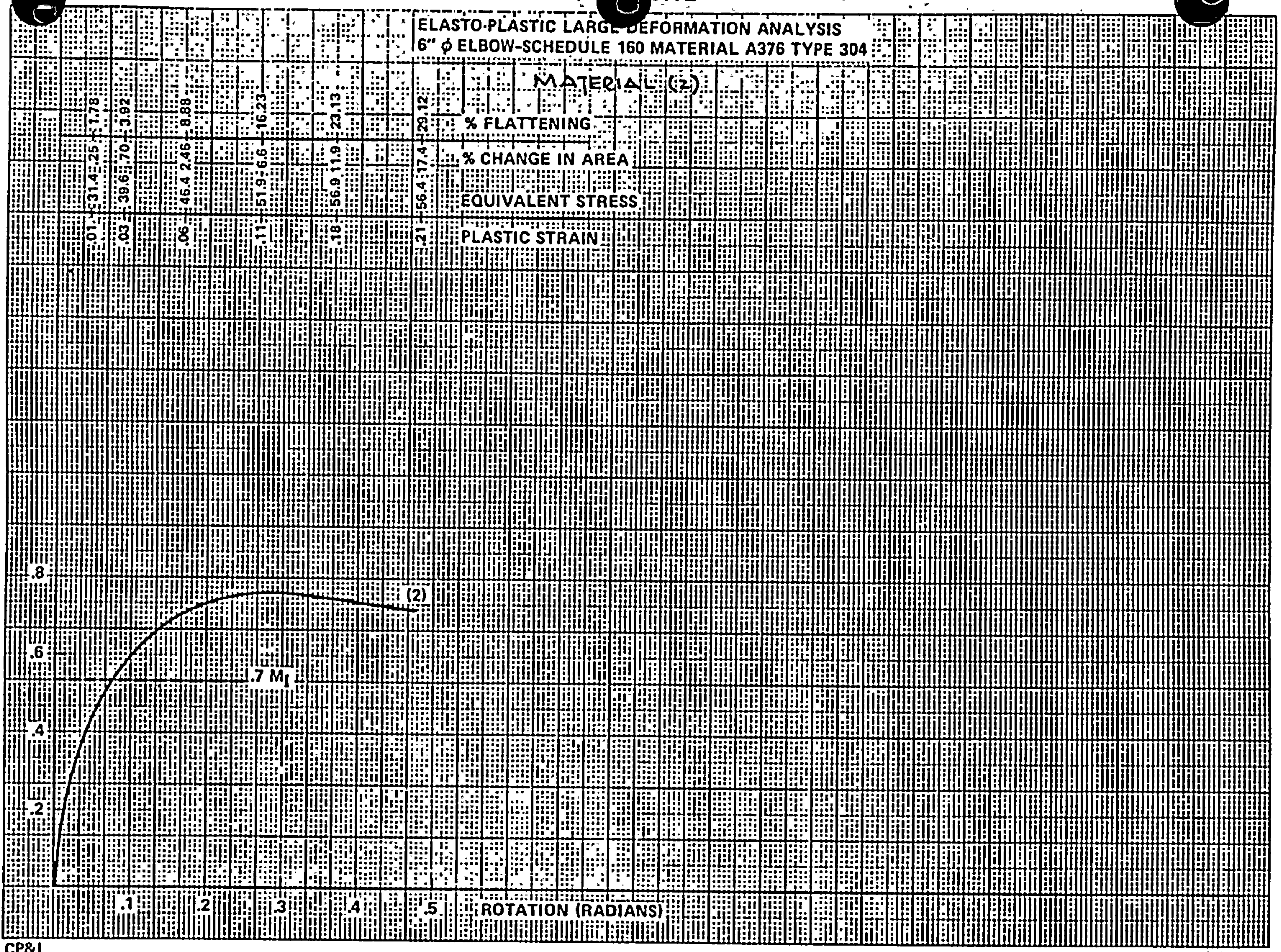
F[illegible]E A-2



ELASTO-PLASTIC LARG[illegible] DEFORMATION ANALYSIS
6" ϕ ELBOW-SCHEDULE 160 MATERIAL A376 TYPE 304

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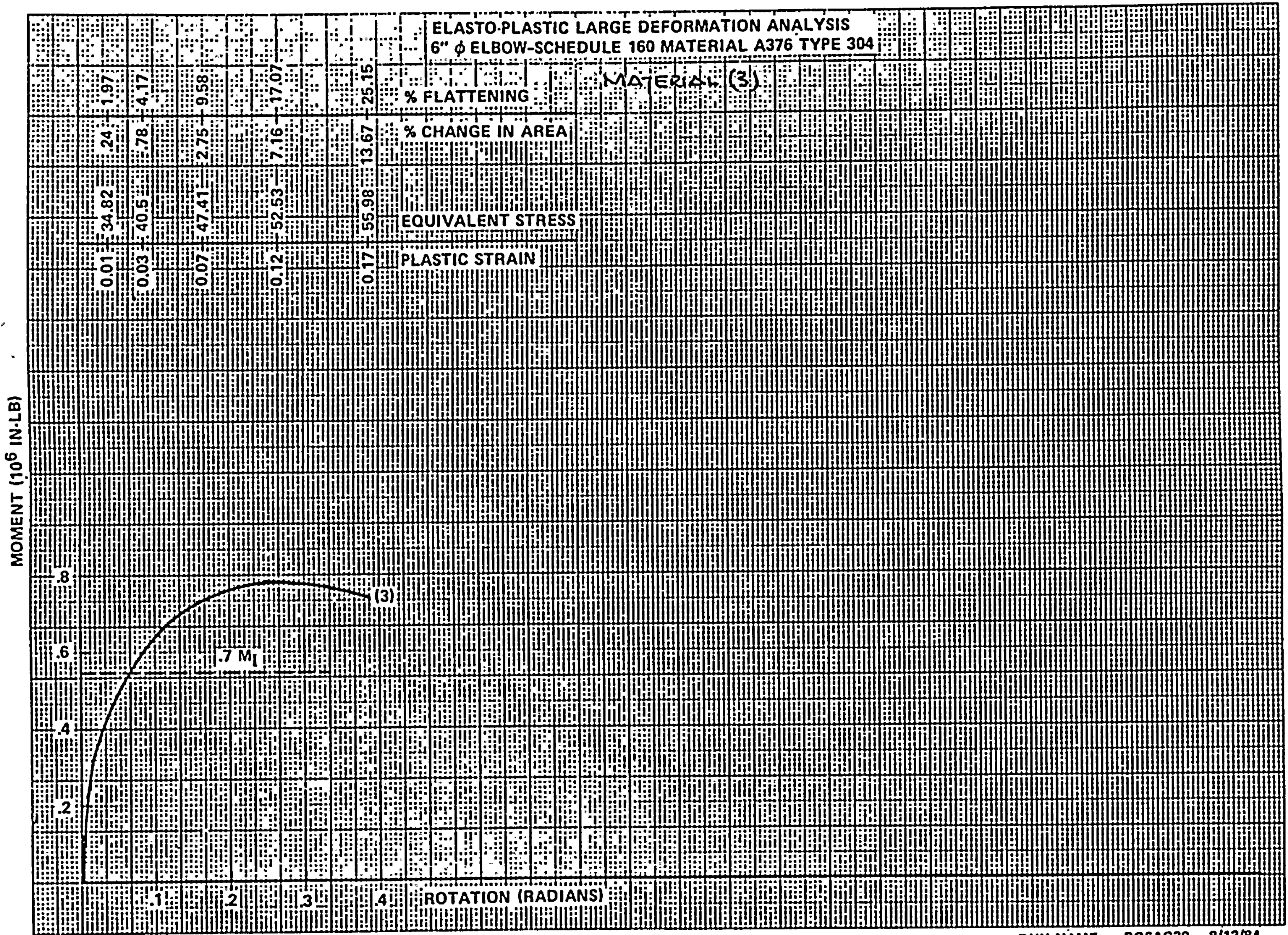
RUN NAME: BO6AGXX 8/8/84

FIGURE A-3



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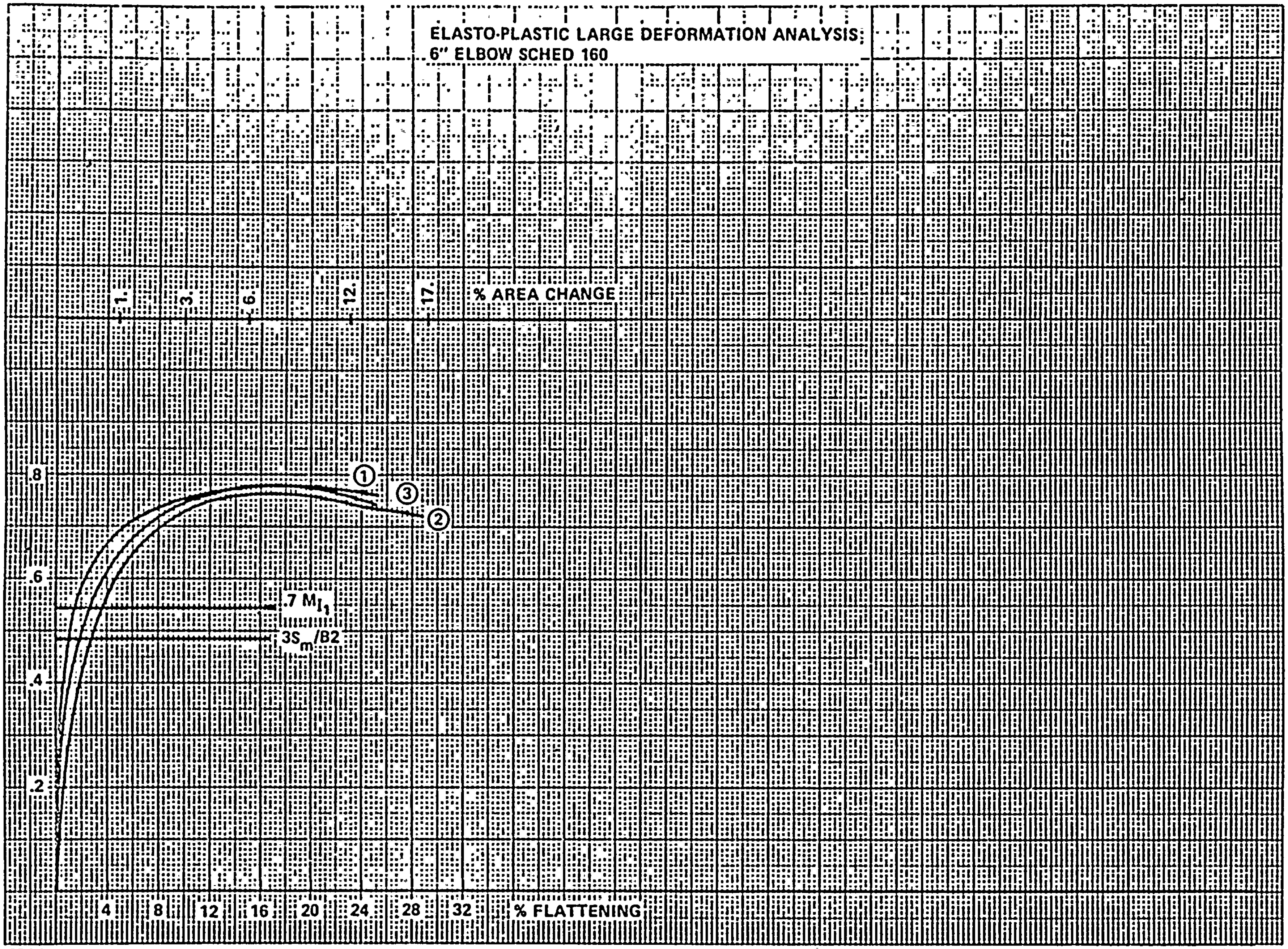
RUN NAME: BO6AG39 8/12/84

FI[illegible]E A-4



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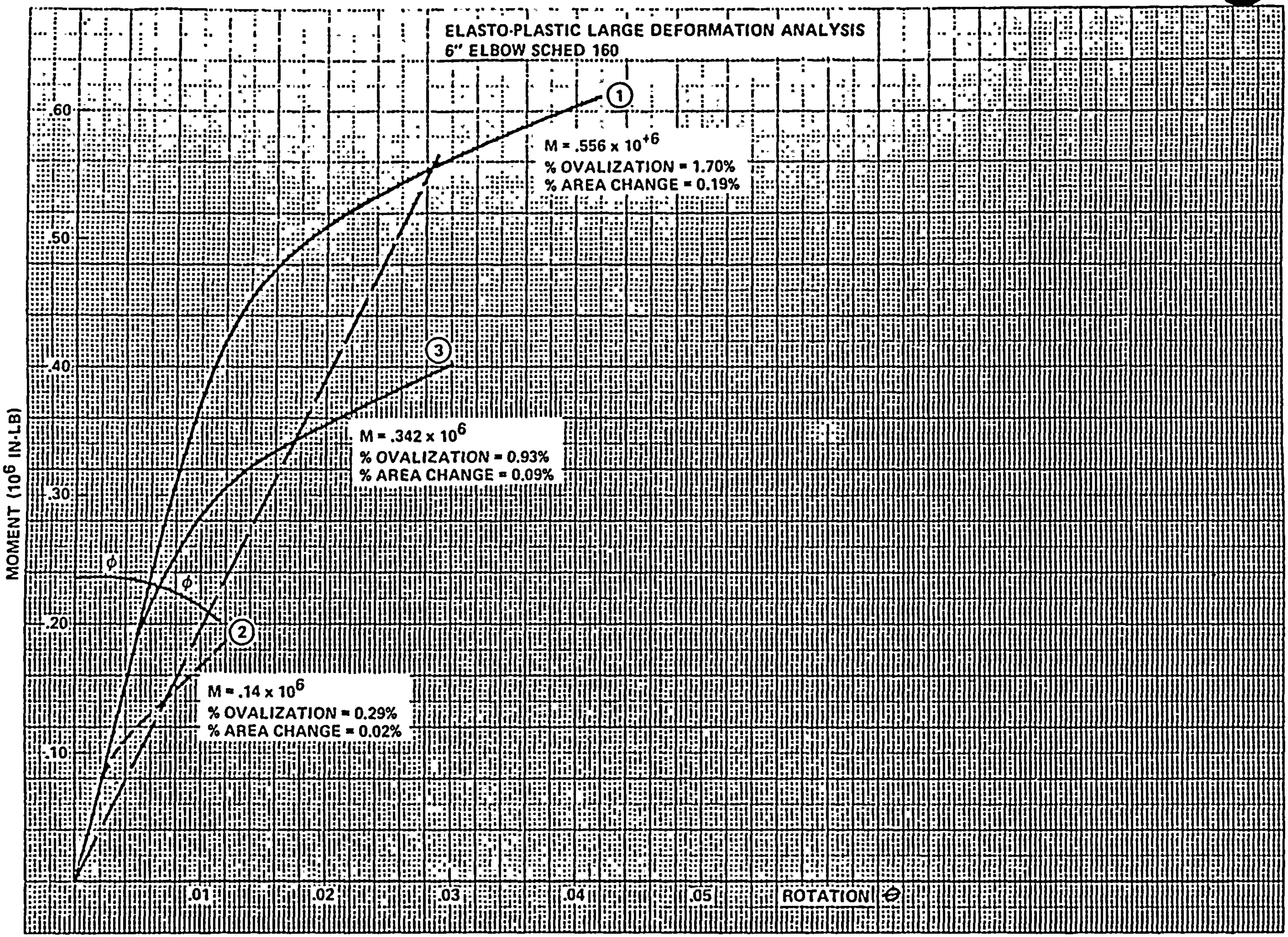
RUN NAME: BO6AG87 4/7/84
BO6AGXX 8/8/84
BO6AG39 8/12/84

FIGU[illegible]-5



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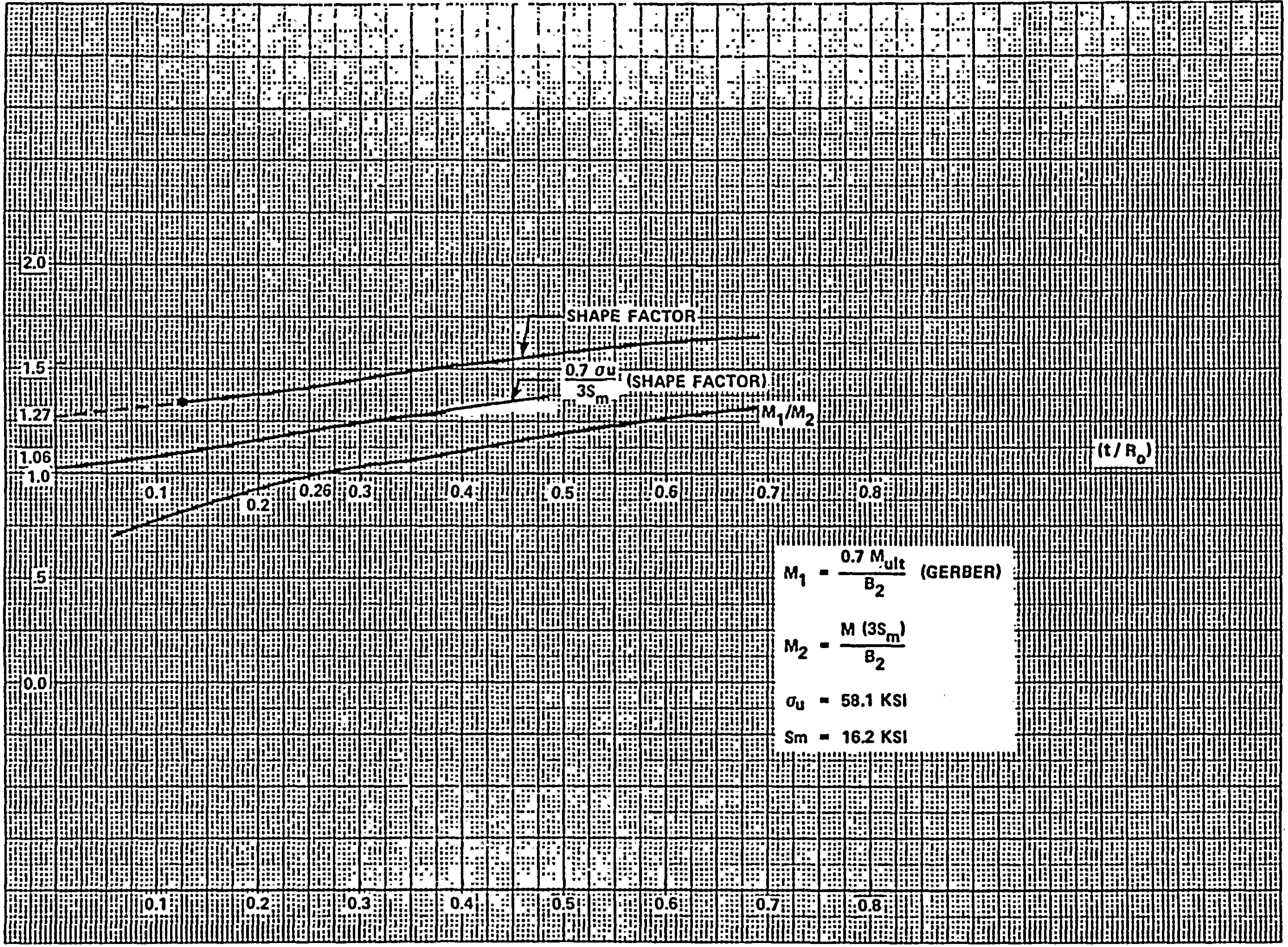
RUN NAME: BO6AG87 4/7/84 BO6AG39 8/11/84
BO6AG1R 8/3/84
BO6AGXX 8/8/84

FIGURE A-6

CONVENTIONAL [illegible]PE FUNCTION VERSUS GERBER'S "SHA[illegible]UNCTION" FOR PIPES



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SHEARON HARRIS NUCLEAR POWER PLANT
FUNCTIONAL CAPABILITY OF ASME CLASS 1
AUXILIARY PIPING SYSTEMS

TABLE A-1
OVALIZATION AND PERCENT CHANGE IN AREA FOR 6" ELBOW USING DIFFERENT ELASTO-PLASTIC MATERIAL PROPERTIES FOR "LIMIT" MOMENTS

APPROACH		ELASTIC	PLASTIC (FINITE ELEMENT)	
LINE SIZE & ELBOW PARAMETERS	COMPARISON PARAMETERS	$M(3S_m)/B2$ 10^6 in-lb	$0.7M_I$ 10^6 in-lb	M_c
6"	Moment	0.485	0.541	0.556
Material (1)				
$B_2 = 1.7864$	Ovalization	0.85%	1.45%	1.70%
$t/R = 0.2434$	Area Change	0.07%	0.17%	0.19%
6"	Moment	0.485	0.534	0.14
Material (2)				
$B_2 = 1.7864$	Ovalization	2.62%	3.42%	0.29%
$t/R = 0.2434$	Area Change	0.41%	0.59%	0.02%
6"	Moment	0.485	0.547	0.342
Material (3)				
$B_2 = 1.7864$	Ovalization	2.25%	3.08%	0.93%
$t/R = 0.2434$	Area Change	0.31%	0.48%	0.09%

TABLE F-1322.2-1
LIMITS OF PRIMARY LOAD OR STRESS FOR SERVICE LOADINGS WITH LEVEL D SERVICE LIMITS

Method of Analysis		Load or Stress [Note (6)]	Design Limits	
System F-1322.1	Component F-1322.2		Components [Notes (3)/(6)]	Component Supports [Note (3)]
Elastic	Elastic	Stress NB-3221, NB-3230 F-1323.1	$2.4S_m$ } ** $0.7S_u$ } for materials Table I-1.2 } [Note (1)] $0.7S_u$ } for materials Table I-1.1 } Alternative Limits: Valves (F-1350), in preparation Piping (F-1360), pressure ≤2 × Design Pressure $3.0S_m$ [Eq. (9), NB-3652]	$1.5S_m$ } * $1.2S_y$ } but not $>0.7S_u$ [Note (1)]
	Collapse load NB-3213.22	Load P F-1323.2 [Note (7)]	$0.9P_c$ based on $S_y = 2.3S_m$ or on P_c derived from F-1321.1(d) or F-1321.3(a) [Notes (2), (7)]	$1.5S_m$ } * $1.2S_y$ } but not $>0.7S_u$ [Note (1)]
	Stress ratio F-1321.2(a)	Load P_r, stress S_{ae} F-1321.2(c) F-1323.3	$3.0S_m$ } ** $0.7S_u$ } for loads P_r [Note (4)]	Same as components
Inelastic	Elastic	Stress F-1324.1	$0.7S_u$ } * [Note (1)] $S_y + (S_u - S_y)/3$ }	$0.7S_u$ } * [Note (1)] $S_y + (S_u - S_y)/3$ }
	Collapse load	Load P F-1324.2	$0.9P_c$ based on $S_y = 2.3S_m$ or on P_c derived from F-1321.1(d) or F-1321.3(a)	$1.5S_m$ } * $1.2S_y$ } but not $>0.7S_u$
	Stress ratio	Load P_r, stress S_{ae} F-1324.3	$3.0S_m$ } ** $0.7S_u$ } for loads P_r [Note (4)]	Same as components
	Plastic instability F-1321.1(e)	Load P F-1324.4	$0.7P_I$ or loads $P \le P_m$, where $P_m = S_y + (S_t - S_y)/3$ [Note (5)]	Same as components
	Strain limit load	Load P F-1321.1(f) F-1324.5	$0.7P_I$ or loads $P \le P_m$, where $P_m = S_y + (S_t - S_y)/3$, but not $>P_\epsilon$ [Note (8)]	Same as components
	Inelastic	Stress F-1324.6	$0.7S_u$ } * [Note (1)] $S_y + (S_u - S_y)/3$ }	Same as components

* Use greater of limits specified.
** Use lesser of limits specified.

NOTES:

(1) S_u value at temperature shall be specified and justified in Design Report.

(2) P_c denotes the collapse load based on lower bound theorem of limit analyses or as defined in F-1321.1(d).

(3) The Design Limits selected from this Table shall be used in conjunction with F-1323 and F-1324, as applicable, in order to determine the limits for P_m, P_L, and P_b.

(4) Higher limits for S_{ae} may be used as specified in A-9000, where the type of stress field is taken into account.

(5) S_t is the true effective stress associated with plastic instability (F-1324.4).

(6) For compressive loads or stresses, the stability requirements of F-1325 shall be met.

(7) This method is not permitted if deformation limits are stated in Design Specifications.

(8) P_ϵ denotes the load associated with the strain limit placed on the component [F-1321.1(f)].