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MEMORANDUM REPORT ARBRL-MR-03129

STRESS ANALYSIS AND MODIFICATION OF THE M-11 COPPER CRUSHER GAGE

James M. Bender

September 1981

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER MEMORANDUM REPORT ARBRL-MR-03129	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* STRESS ANALYSIS AND MODIFICATION OF THE M-11 COPPER CRUSHER GAGE		5. TYPE OF REPORT & PERIOD COVERED Memorandum Report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) James M. Bender		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Ballistic Research Laboratory ATTN: DRDAR-BLI Aberdeen Proving Ground, MD 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1L162618AH80
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Armament Research & Development Command US Army Ballistic Research Laboratory ATTN: DRDAR-BL Aberdeen Proving Ground, MD 21005		12. REPORT DATE SEPTEMBER 1981 13. NUMBER OF PAGES 32
14. MONITORING AGENCY NAME & ADDRESS*(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Tarage
Finite Element

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)* jmk

A stress analysis on the M-11 Copper Crusher Gage was performed to determine possible flaws in design which prevent repeatability of pressure measurements. As a result of the analysis, a modification was made to the design.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

The Ballistic Research Laboratory (BRL) of the Army Armament Research and Development Command was asked to perform appropriate analysis and recommend modification for improving performance and extending the operating range of the M-11 Copper Crusher Gage by the Materiel Testing Directorate (MTD) of the Test and Evaluation Command. This report discusses the analysis performed and the modification recommended in response to MTD's request.

The M-11 Copper Crusher Gage is a device which measures peak pressure developed in the chamber of large caliber weapons. This gage is one of two models used by the U.S. Army in testing gun systems and is used for high pressure measurements between 150 and 550 MPa.

In the Third NATO Crusher Gage Comparison Trials held at Meppen, Federal Republic of Germany in October 1977, the M-11 Copper Crusher Gage did not meet the precision requirements set forth by NATO. The precision of the gage was deficient at pressures in excess of 350 MPa for test temperatures of -40°C, -10°C, and 60°C (-40°F, -14°F, and 140°F). Ambient temperature tests at 21°C (70°F) yielded satisfactory results.

The objective of the effort discussed in this report is to determine through analysis the appropriate modification required to cause the M-11 Copper Crusher Gage to satisfactorily meet all of the NATO standards of precision for crusher gages and to extend the operating range to 827 MPa (120,000 psi).

II. COPPER CRUSHER GAGE

A. Construction and Assembly

The M-11 Copper Crusher Gage is a totally self contained unit, which is basically cylindrical in shape with steel parts fabricated from 300 grade maraging steel. It measures 38 mm (1.50 in.) in length and 19 mm (0.75 in.) in diameter. The gage consists of a body, cap, and other inner working components as shown in Figure 1. The end opposite the cap is bored axially and fitted with a piston. The dimensions of the piston and bore are such that a good seal is maintained yet low-friction operation is permitted. Inside, the piston rests gently against a copper sphere, the primary sensing element, which measures 4.75 mm (.1875 in.) in diameter. The sphere is supported on the opposite side by the anvil face of the cap. The sphere, resting between the piston and anvil, is centered by a triangular-shaped spring so that it is held directly on the centerline of the piston. The cap is easily removed to permit access to all of these components. Finally, copper bands are swaged on to each end of the gage body to absorb shock should the gage happen to strike the inside wall of the gun tube when the weapon is fired.

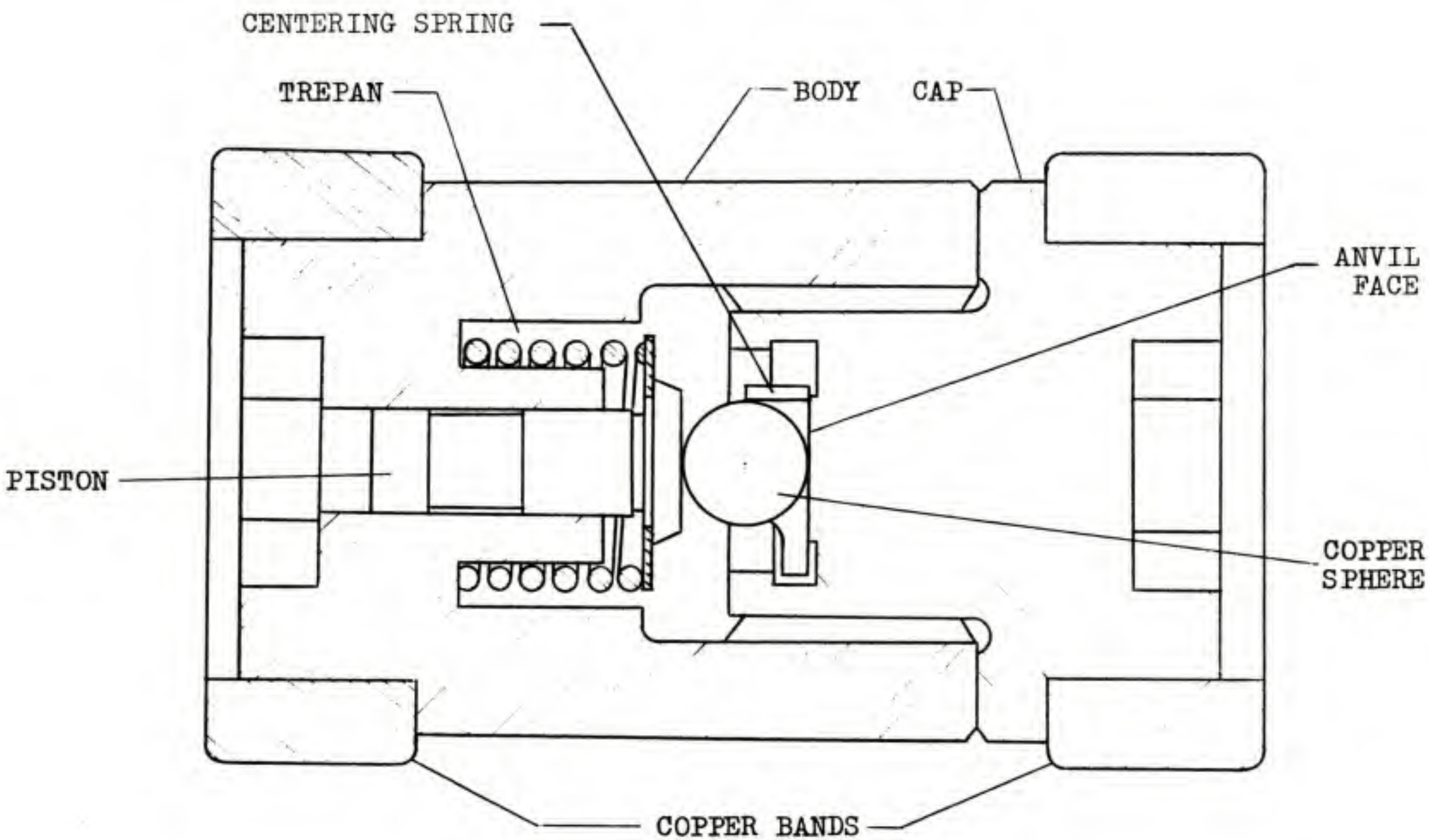

Figure 1. Assembly Sketch of M-11 Copper Crusher

B. Operation

After careful assembly, the free end of the piston is sealed with silicone. Normally, two gages are placed in the cartridge case with the charge before loading. The round is then assembled and loaded. When the weapon is fired, the pressure developed in the chamber acts against the free end of the piston which in turn pushes against the copper sphere, plastically deforming it. The gages are retrieved and taken to the lab where they are disassembled and the copper spheres removed. The sphere, which is partially to substantially flattened, depending on pressure, is measured in the direction of the crush. The final height measurement is located on the tarage table and the corresponding pressure read.

C. Tarage Table

A tarage table is developed for each lot of spheres and is supplied by the manufacturer. It is a table of "Final Height" vs. "Chamber Pressure". The table is developed as follows. A hydraulic testing device is used to simulate the pressure-time history pulse developed by a large caliber weapon. A piezoelectric element, the accepted standard for pressure measuring devices, is used to accurately measure pressure in the test chamber. Several gages are placed in the test chamber along with the piezoelectric element. The pressure pulse is then applied to the chamber, acting simultaneously on the gages and piezoelectric element. The spheres are removed from the gages, measured for final height, averaged and entered on a table opposite the pressure reading registered by the piezoelectric element. The values from the table are plotted on a graph through which a fifth degree regression curve is fitted (See sample shown in Figure 2, note that "remaining length" and "final height" mean the same thing). This curve is used to generate a table of values of "Final Height" vs. "Pressure" at intervals of 0.0001 in. of final height from 0.0930 in. to 0.1770 in. A portion of that table is shown as Table 1 (The English units have been retained in this table, preserving those originally used). Should the gages be used at other than ambient temperature of 21°C (70°F) a temperature correction factor must be used to modify the reading from the tarage table.

D. Temperature Correction Factor

Due to the effects of temperature change on metals, a temperature correction factor is needed to correct all pressure readings to the 21°C standard. This correction factor is determined by the following procedure. Several gages are allowed to soak at each of the test temperatires of -40°C, - 10°C, 21°C and 60°C prior to testing. Then at each temperature the gages are tested against the piezoelectric standard at approximately 50 MPa intervals along the entire operating range of the gage. A plot of "piezo pressure" vs. "crusher pressure" is made for each test temperature and a second order regression curve fitted to those points as shown in Figure 3. From those curves a table of "pressure" vs.

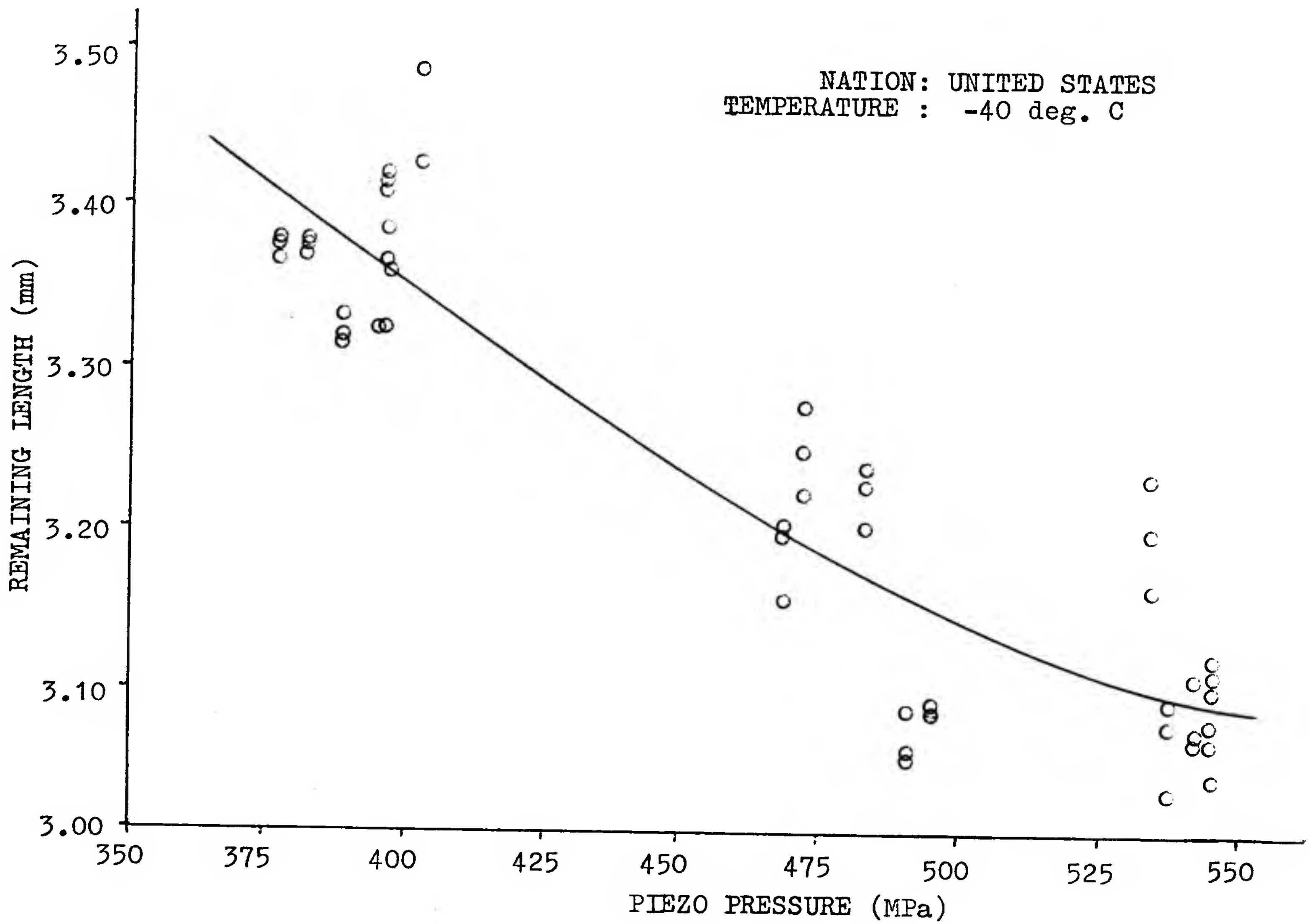

Figure 2. Pressure vs. Remaining Length for M-11 Copper Crusher

TABLE 1. **DYNAMIC TARAGE TABLE**

Chamber Pressure (psi in thousands) vs Compressed Height

of 3/16-inch Copper Sphere (inches)

For Use With Gages Having 1/60 Square Inch Piston

Sphere Dwg No. A7581425 Lot APG 2-75

Final Height, inches	.0000	.0001	.0002	.0003	.0004	.0005	.0006	.0007	.0008	.0009
.093	115.8	115.6	115.3	115.1	114.9	114.6	114.4	114.2	113.9	113.7
.094	113.5	113.3	113.0	112.8	112.6	112.3	112.1	111.9	111.7	111.4
.095	111.2	111.0	110.8	110.6	110.3	110.1	109.9	109.7	109.5	109.2
.096	109.0	108.8	108.6	108.4	108.2	108.0	107.7	107.5	107.3	107.1
.097	106.9	106.7	106.5	106.3	106.1	105.8	105.6	105.4	105.2	105.0
.098	104.8	104.6	104.4	104.2	104.0	103.8	103.6	103.4	103.2	103.0
.099	102.8	102.6	102.4	102.2	102.0	101.8	101.6	101.4	101.2	101.0
.100	100.8	100.6	100.4	100.2	100.0	99.9	99.7	99.5	99.3	99.1
.101	98.9	98.7	98.5	98.3	98.1	98.0	97.8	97.6	97.4	97.2
.102	97.0	96.8	96.7	96.5	96.3	96.1	95.9	95.7	95.6	95.4
.103	95.2	95.0	94.8	94.6	94.5	94.3	94.1	93.9	93.8	93.6
.104	93.4	93.2	93.0	92.9	92.7	92.5	92.3	92.2	92.0	91.8
.105	91.7	91.5	91.3	91.1	91.0	90.8	90.6	90.5	90.3	90.1
.106	89.9	89.8	89.6	89.4	89.3	89.1	88.9	88.8	88.6	88.4
.107	88.3	88.1	87.9	87.8	87.6	87.5	87.3	87.1	87.0	86.8
.108	86.6	86.5	86.3	86.2	86.0	85.8	85.7	85.5	85.4	85.2
.109	85.0	84.9	84.7	84.6	84.4	84.3	84.1	83.9	83.8	83.6
.110	83.5	83.3	83.2	83.0	82.9	82.7	82.6	82.4	82.2	82.1
.111	81.9	81.8	81.6	81.5	81.3	81.2	81.0	80.9	80.7	80.6
.112	80.4	80.3	80.1	80.0	79.8	79.7	79.5	79.4	79.3	79.1
.113	79.0	78.8	78.7	78.5	78.4	78.2	78.1	77.9	77.8	77.7
.114	77.5	77.4	77.2	77.1	76.9	76.8	76.7	76.5	76.4	76.2
.115	76.1	75.9	75.8	75.7	75.5	75.4	75.2	75.1	75.0	74.8
.116	74.7	74.6	74.4	74.3	74.1	74.0	73.9	73.7	73.6	73.5
.117	73.3	73.2	73.0	72.9	72.8	72.6	72.5	72.4	72.2	72.1
.118	72.0	71.8	71.7	71.6	71.4	71.3	71.2	71.0	70.9	70.8
.119	70.6	70.5	70.4	70.2	70.1	70.0	69.9	69.7	69.6	69.5
.120	69.3	69.2	69.1	68.9	68.8	68.7	68.6	68.4	68.3	68.2
.121	68.0	67.9	67.8	67.7	67.5	67.4	67.3	67.2	67.0	66.9
.122	66.8	66.7	66.5	66.4	66.3	66.2	66.0	65.9	65.8	65.7
.123	65.5	65.4	65.3	65.2	65.0	64.9	64.8	64.7	64.5	64.4
.124	64.3	64.2	64.1	63.9	63.8	63.7	63.6	63.4	63.3	63.2
.125	63.1	63.0	62.8	62.7	62.6	62.5	62.4	62.2	62.1	62.0
.126	61.9	61.8	61.7	61.5	61.4	61.3	61.2	61.1	60.9	60.8
.127	60.7	60.6	60.5	60.4	60.2	60.1	60.0	59.9	59.8	59.7
.128	59.5	59.4	59.3	59.2	59.1	59.0	58.9	58.7	58.6	58.5
.129	58.4	58.3	58.2	58.1	57.9	57.8	57.7	57.6	57.5	57.4
.130	57.3	57.2	57.0	56.9	56.8	56.7	56.6	56.5	56.4	56.3
.131	56.1	56.0	55.9	55.8	55.7	55.6	55.5	55.4	55.3	55.1
.132	55.0	54.9	54.8	54.7	54.6	54.5	54.4	54.3	54.2	54.1
.133	53.9	53.8	53.7	53.6	53.5	53.4	53.3	53.2	53.1	53.0
.134	52.9	52.8	52.6	52.5	52.4	52.3	52.2	52.1	52.0	51.9
.135	51.8	51.7	51.6	51.5	51.4	51.3	51.2	51.1	50.9	50.8

Calibrated at Aberdeen Proving Ground, MD, Aug 75.

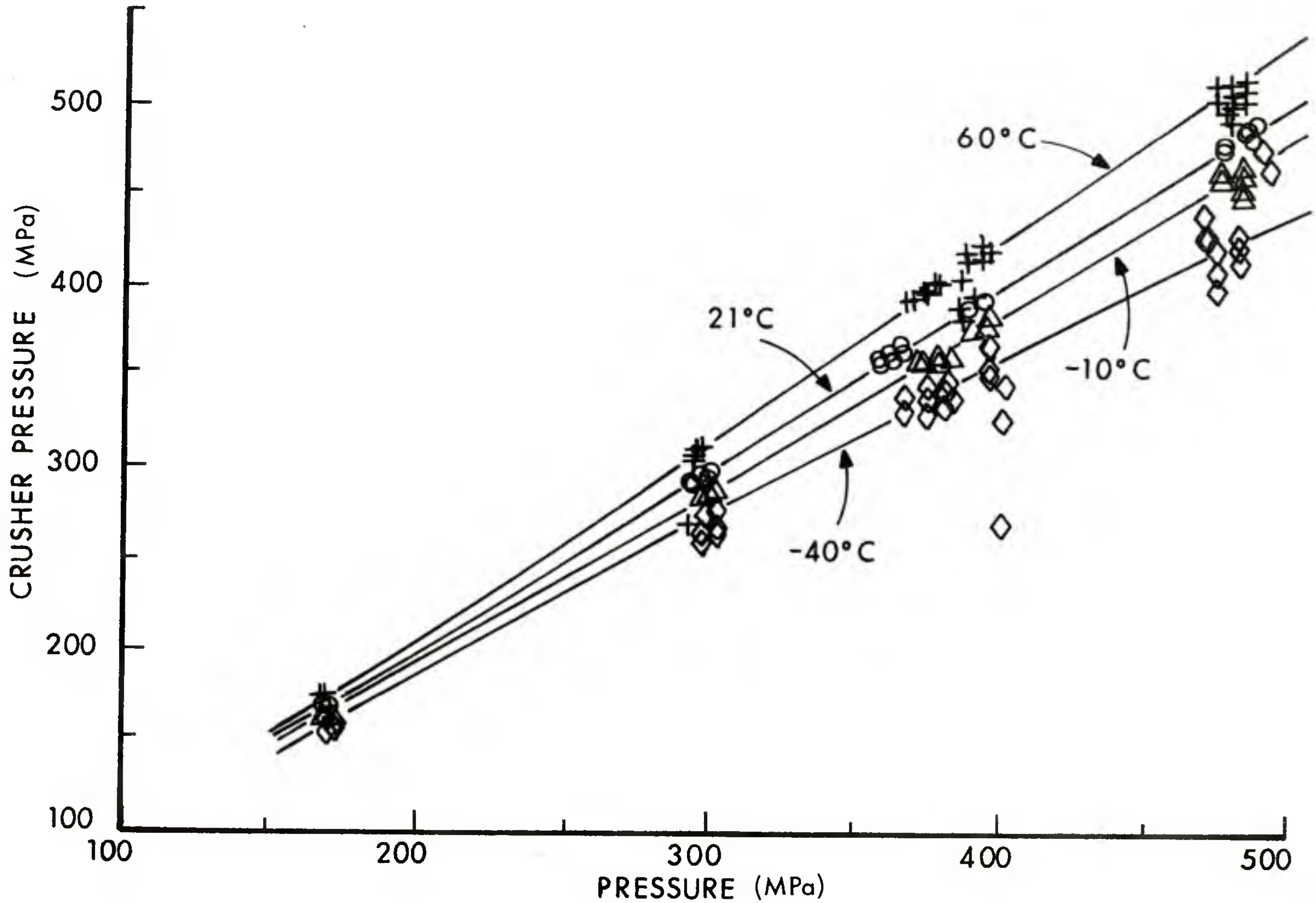

Figure 3. Crusher Pressure vs. Piezo Pressure

TABLE 2. TEMPERATURE CORRECTION FACTORS

Pressure Range: 120 to 190 MPa

MPa	21°C	-40°C	-10°C	60°C
120	1.000	0.917	0.958	1.044
130	1.000	.912	.958	1.049
140	1.000	.908	.958	1.054
150	1.000	.904	.957	1.059
160	1.000	.899	.957	1.065
170	1.000	.895	.957	1.070
180	1.000	.890	.957	1.076
190	1.000	.885	.957	1.081
Pressure Range: 180 to 560 MPa				
180	1.000	0.931	0.972	1.026
190	1.000	.931	.969	1.027
200	1.000	.931	.968	1.027
210	1.000	.931	.966	1.028
220	1.000	.930	.965	1.029
230	1.000	.929	.963	1.030
240	1.000	.928	.962	1.030
250	1.000	.927	.962	1.031
260	1.000	.926	.961	1.032
270	1.000	.924	.960	1.033
280	1.000	.923	.960	1.034
290	1.000	.922	.959	1.035
300	1.000	.920	.959	1.036
310	1.000	.918	.959	1.038
320	1.000	.917	.959	1.039
330	1.000	.915	.959	1.040
340	1.000	.913	.959	1.041
350	1.000	.911	.959	1.042
360	1.000	.909	.959	1.044
370	1.000	.907	.959	1.045
380	1.000	.905	.959	1.046
390	1.000	.903	.959	1.047
400	1.000	.901	.959	1.049
410	1.000	.899	.960	1.050
420	1.000	.897	.960	1.051
430	1.000	.895	.960	1.052
440	1.000	.893	.961	1.054
450	1.000	.891	.961	1.055
460	1.000	.889	.962	1.056
470	1.000	.886	.962	1.058
480	1.000	.884	.962	1.059
490	1.000	.882	.963	1.060
500	1.000	.880	.963	1.062
510	1.000	.877	.964	1.063
520	1.000	.875	.964	1.065
530	1.000	.873	.965	1.066
540	1.000	.870	.966	1.067
550	1.000	.868	.966	1.069
560	1.000	.866	.967	1.070

"correction factor" is generated for each temperature as Table 2. The correction factor, f_t, is equal to crusher pressure divided by piezo pressure. The pressure reading obtained from the crushed spheres is then multiplied by the appropriate correction term, depending on temperature, to obtain the corrected or "true" pressure.

III. FINITE ELEMENT STRESS ANALYSIS

The BRLESC Finite Element Program[1], as modified for BRL's CDC computer, was used to determine variations in the behavior of the M-11 Copper Crusher Gage due to temperature and pressure extremes. This axisymmetric finite element stress analysis program is a version of the SAAS II code[2].

A. Grid and Loading

A partial cross section of the M-11 Copper Crusher Gage divided into finite elements, is shown in Figure 4. The entire exterior of the gage and the free end of the piston were loaded to 550 MPa and subjected to a temperature change from 21°C to -40°C. At the crushing end of the piston an equal and opposing force was applied to account for the sphere's reaction to the pressure. This condition was examined because it represented the worst case as far as precision is concerned in the aforementioned comparison trials. Figure 5 shows the result of the loading. The deformed figure (1000% exaggerated for clarity) is superimposed on the outline of the undeformed figure.

B. Response

It was suspected that the high pressure exerted on the gage body was of sufficient magnitude to partially clamp the piston before it was permitted its full travel. Figure 5 shows that this does in fact occur. The output was scaled to show overlap as a representation of interference. The radial clearances between the piston and bore wall at selected points are listed in Table 3. These measurements start at the crushing end and proceed toward the anvil end.

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[1] *S. G. Sawyer, "BRLESC Finite Element Program for Axisymmetric Plane Strain, and Plane Stress, Orthotropic Solids with Temperature-Dependent Material Properties". BRL Report #1539, Ballistic Research Laboratories, Aberdeen Proving Ground, MD (March 1971) AD #727702.*

[2] *R. M. Jones, J. G. Crose, "SAAS II Finite Element Stress Analysis of Axisymmetric Solids with Orthotropic, Temperature Dependent Material Properties", Aerospace Corporation, San Bernadino, California to Air Force Systems Command, Washington, D.C. September 1968.*

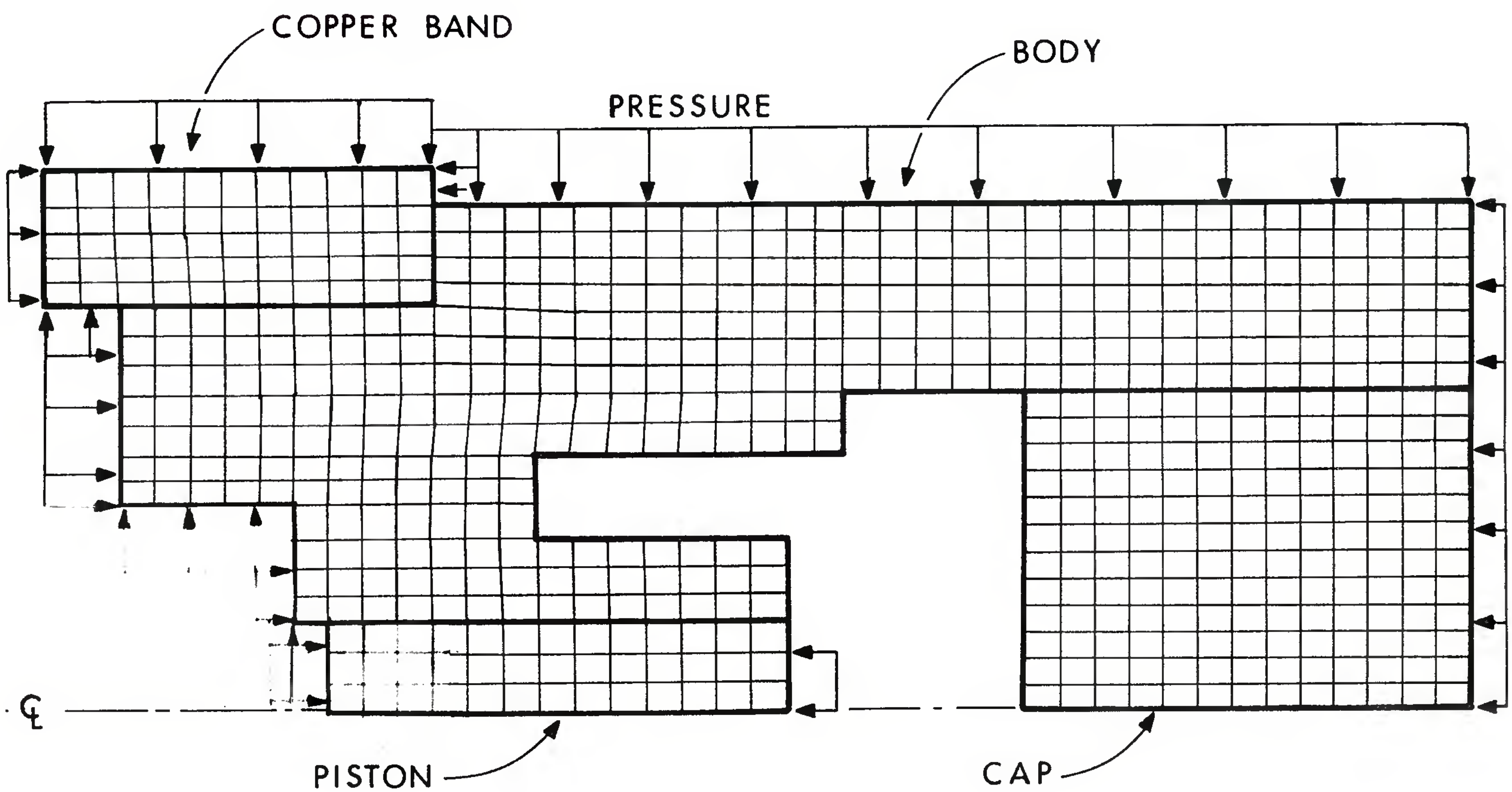

Figure 4. Finite Element Grid of Copper Crusher With Loading Scheme

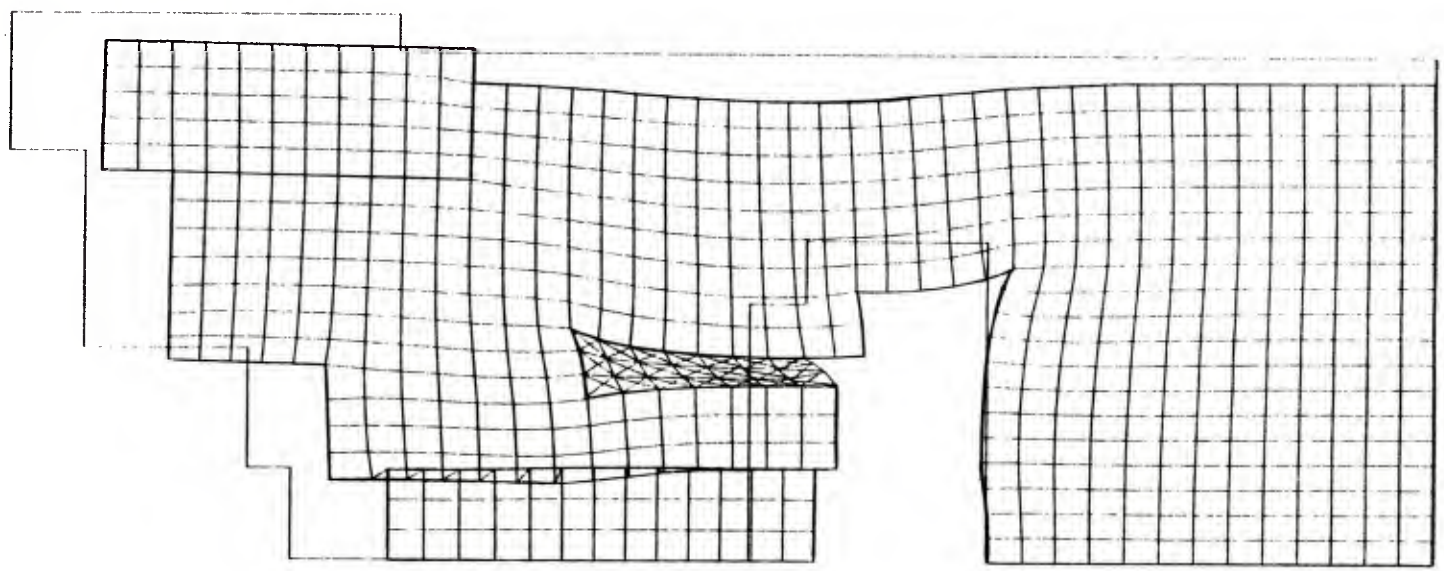

Figure 5. Deformed Finite Element Grid; Result of 550 MPa at -40°C

TABLE 3. PISTON CLEARANCES OF M-11

DISTANCE FROM CRUSHING END mm	DISTANCE FROM CRUSHING END in.	RADIAL CLEARANCE mm	RADIAL CLEARANCE in.
0.000	0.000	0.0076	0.000300
0.711	0.028	0.0064	0.000250
1.448	0.057	0.0062	0.000245
2.159	0.085	0.0062	0.000246
2.896	0.114	0.0056	0.000220
3.607	0.142	0.0051	0.000200
4.343	0.171	0.0033	0.000130
5.080	0.200	0.0013	0.000050
5.766	0.227	-0.0011	-0.000045
6.426	0.253	-0.0027	-0.000105
7.112	0.280	-0.0038	-0.000150
7.823	0.308	-0.0043	-0.000170
8.560	0.337	-0.0042	-0.000165
9.271	0.365	-0.0030	-0.000120

Since the piston is partially clamped, it cannot transfer all of the pressure to the sphere. Therefore, the crushed sphere would indicate less than true pressure. However, noting the designer tolerances of piston and bore diameters (piston diameter is 3.698 ± 0.003 mm (0.1456 ± 0.0001 in.), bore diameter is 3.712 ± 0.004 mm (0.14615 ± 0.00015 in.)), it is possible that many gages may have a small diameter piston and large diameter bore, both within tolerances. This would alleviate the binding in this case and the piston would transmit true pressure. This suggests why several gages can behave differently for the same applied pressure, yielding scattered data and poor repeatability. (Note the scattered data in Figure 2). For example, a small piston fitted with a large bore would allow 0.0032 mm (0.000126 in.) additional clearance and allow the gage to function properly. Similar scatter is also found in the temperature correction factor curves shown in Figure 3. The piston and bore diameters used in the finite element grid shown in Figure 4 were the mean values of the tolerances given.

From the results of the high temperature tests, it was determined that the temperature affects only the ease or difficulty with which the sphere is crushed (metal strength decreases with an increase in temperature) and not the operation of the gage where extreme pressure is the overwhelming factor. A test performed applying a temperature change of

± 60°C and zero pressure did not significantly change the fifth decimal place digit to the right of the decimal in the piston/bore clearance measurements.

C. Modification

With the aid of the finite element results, it was determined that by shortening the piston and deepening the trepan (see Figure 1) the piston was more isolated from the binding effects of the applied pressure and allowed to operate more freely. It was decided to test the gage at the higher required pressure of 817 MPa since new weapons may generate this pressure. The result is shown in Figure 6. The elements marked with an "X" are air or have been redesignated as air from steel in the piston. The radial clearances at the nodal points along the piston are listed in Table 4. Since all clearances are positive the gage is expected to function normally.

TABLE 4. PISTON CLEARANCES OF MODIFIED GAGE

DISTANCE FROM CRUSHING END		CLEARANCE	
mm	in.	mm	in.
0.000	0.000	0.0051	0.000200
0.711	0.028	0.0052	0.000206
1.448	0.057	0.0054	0.000212
2.159	0.085	0.0055	0.000215
2.896	0.114	0.0054	0.000213
3.607	0.142	0.0050	0.000197
4.343	0.171	0.0040	0.000158
5.080	0.200	0.0022	0.000086
5.766	0.227	0.0012	0.000046

It was feared that the shortened piston might allow gas intrusion into the gage (pressure blowing by the piston and entering the interior chamber, thus destroying the gage). A test was performed using the finite element program to determine the piston/bore clearances after the piston had actuated. This was accomplished by redesignating the last three sections of the piston as air, simulating an actuated piston (marked by an "X" on the elements in Figure 7). Pressure loads were extended to the area of the bore wall left uncovered by the piston. The results are shown in Figure 8 and clearances tabulated in Table 5.

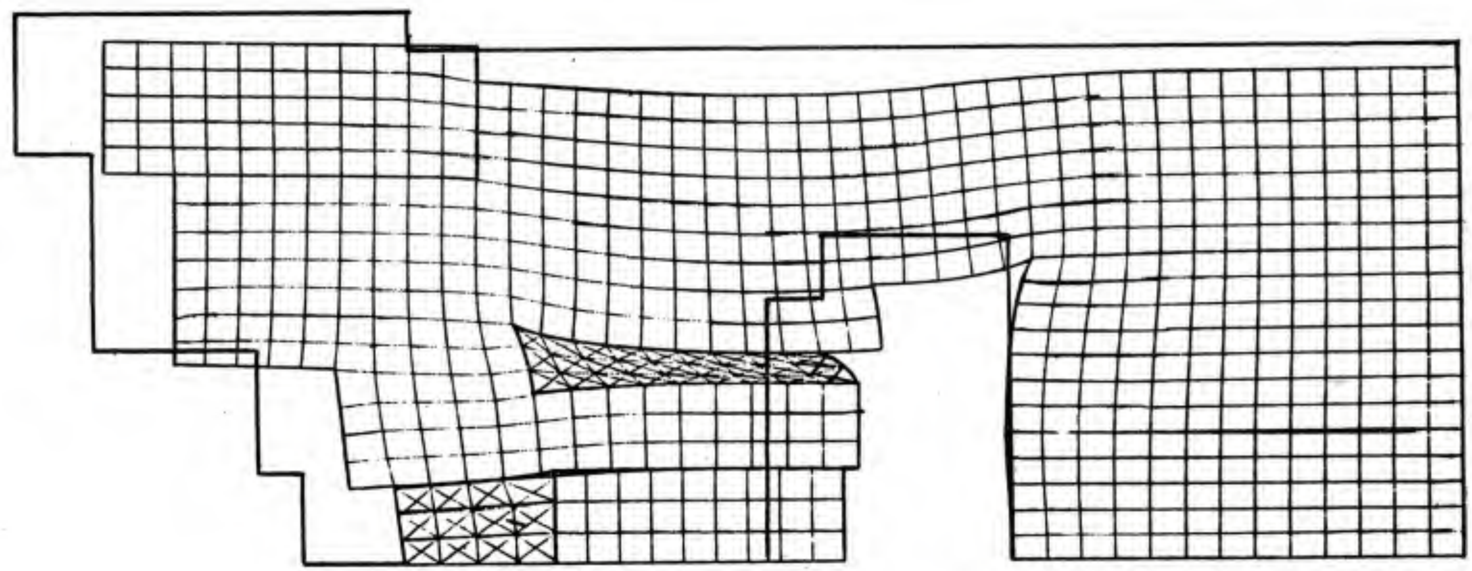

Figure 6. Result of 827 MPa Applied To Modified M-11 Crusher Gage

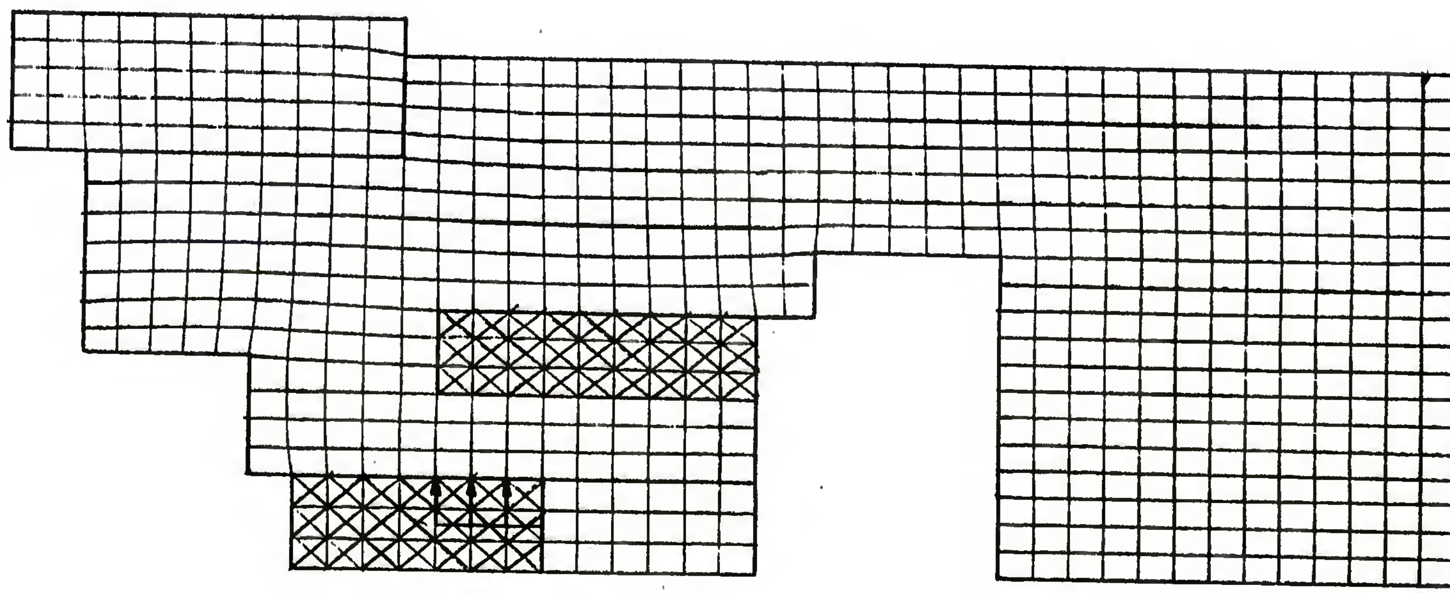

Figure 7. Modified M-11 Gage Showing Actuated Piston

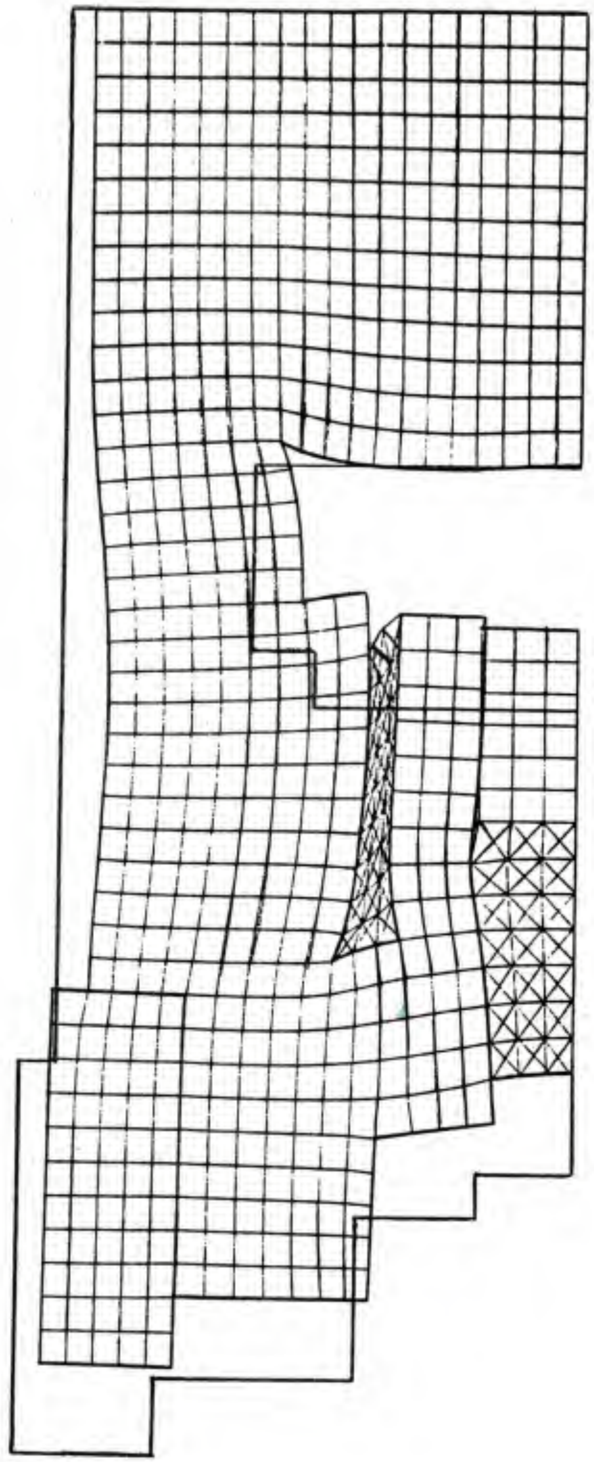

Figure 8. Result of 827 MPa Applied To Modified M-11 Crusher Gage With Actuated Piston

TABLE 5. PISTON CLEARANCES AFTER PISTON ACTUATION

DISTANCE FROM CRUSHING END		CLEARANCE	
mm	in.	mm	in.
0.000	0.000	0.0115	0.000454
0.711	0.028	0.0087	0.000343
1.448	0.057	0.0072	0.000282
2.159	0.085	0.0060	0.000237
2.896	0.114	0.0052	0.000205
3.607	0.142	0.0052	0.000206
4.343	0.171	0.0040	0.000158

Note that the clearance at the first two nodal points along the piston indicates a somewhat large gap, but the clearances at the remaining nodal points are within the original clearance boundaries and should seal the gage from blow-by.

As redesigned, the bore length of the trepan is now 1.3 mm (0.05 in.) deeper while the piston is 2.8 mm (0.11 in.) shorter. The relief band on the piston shaft (Figure 1) has also been eliminated. Its intended function was to reduce the effects of slight bends in the piston. Since the piston has been shortened, the band was deemed unnecessary because any bending deformation within tolerances are insignificant with the reduced length.

IV. DISCUSSION AND CONCLUSIONS

Modifications to the M-11 Copper Crusher gage have been posed, analyzed and suggested for manufacture to extend the pressure range of this type of gage and to improve the reliability of the gage. Although no testing of the revised gage has been conducted yet, the analyses presented here greatly enhance the confidence of achieving operational success with the modified gage.

The analyses performed incorporate limitations which serve as slim structural safety factors. The SAAS II computer program used for these stress analyses is capable of simulating structural response to quasi-static loads. Some metals offer a reserve strength when experiencing a dynamic load of short duration (3 to 5 milliseconds). Since the M-11 gage behaved satisfactorily under a quasi-static load of 827 MPa, it is expected to perform well under dynamic load of the same magnitude. Fatigue effects have not been included.

REFERENCES

1. S. G. Sawyer, "BRLESC Finite Element Program for Axisymmetric Plane Strain, and Plane Stress, Orthotropic Solids with Temperature-Dependent Material Properties", BRL Report #1539, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, March 1971 (AD #727702).

2. R. M. Jones, J. G. Crose, "SAAS II Finite Element Stress Analysis of Axisymmetric Solids with Orthotropic, Temperature Dependent Material Properties", Aerospace Corporation, San Bernadino, California, September 1968.

APPENDIX

APPENDIX

This specification covers the procedure for processing 4.7625 mm (0.1875 - 0.0005 in.) Oxygen Free High Conductivity Copper Balls for Aberdeen Proving Ground.

STEP	DEPARTMENT	SPECIFICATIONS
1	Receiving	1. 0.135 O.F.H.C. Copper Wire. Verify weight, coil and lot identification. 2. Tag each coil by number 1, 2, 3, 4, etc. 3. Cut 2 ft. sample from each end of each coil and identify with coil number. 4. Submit samples of coil ends identified by coil number to Aberdeen Proving Ground for approval. 5. Hold material in Receiving until released by Aberdeen Proving Ground.
2	Heading	1. Head to size -- 0.194 to 0.198 in. 2. Send a minimum of 12 sample headed balls from each coil identified by coil number to Aberdeen Proving Ground for approval. 3. Hold as headed product until approved by Aberdeen Proving Ground.
3	Quality Control	Spot Inspection.
4	Flash	1. Flash to remove trace of equator and poles.
5	Rough Grind	1. Grind to 0.189 in. Special Ball Department (Stone Lap). 2. Barrel Clean.
6	Finish Grind	1. Grind to 0.188 in. Special Ball Department (Stone Lap).
7	Barrel	1. Barrel finish to 0.18725 in. 2. Surface must be smooth and free of cut scratches and defects.
8	Heat Treat	1. Anneal at 750°F for one-half hour at temperature, and water quench (Loads not to exceed 40 lbs.). 2. Barrel Clean.

STEP	DEPARTMENT	SPECIFICATIONS
9	BRIGHT DIP-H_3PO_4	
10	Inspection	1. 100% visual inspect.
11	Pack and Ship	1. See Contract DAAD05-75-B-0047, Sec. G.

NOTE:

Under no circumstance shall lots be mixed during any operation.

Each lot shall represent one coil of material, and shall be identified by the representative coil number.

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