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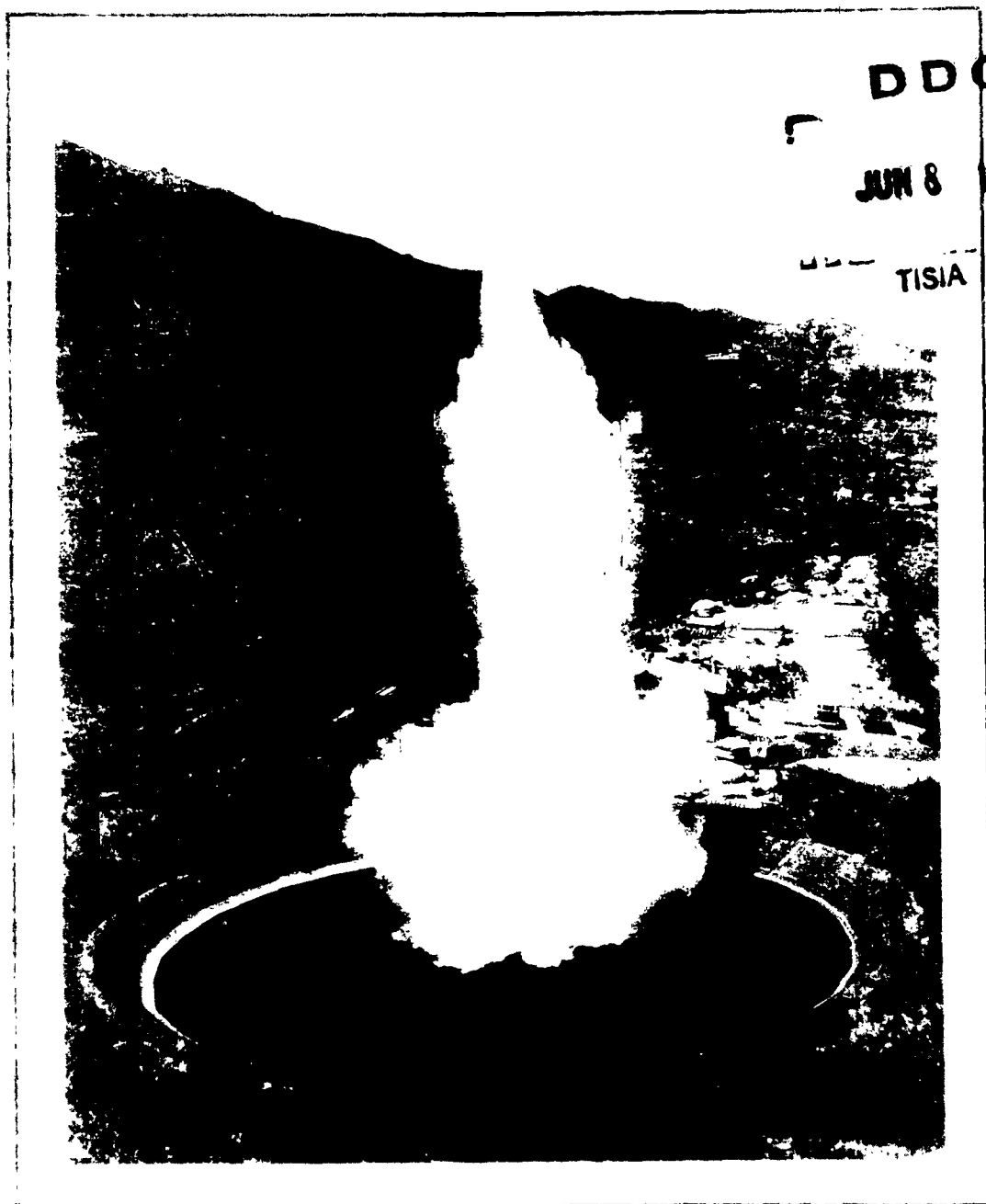
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REVIEW OF EXPLOSIVE (CHEMICAL) FORMING



J. S. ARMY PRODUCTION EQUIPMENT AGENCY
MANUFACTURING TECHNOLOGY DIVISION
ROCK ISLAND ARSENAL, ILLINOIS

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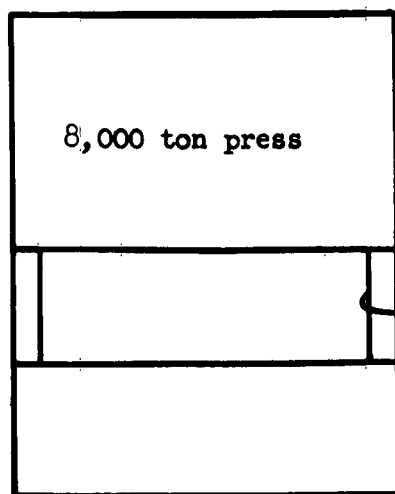
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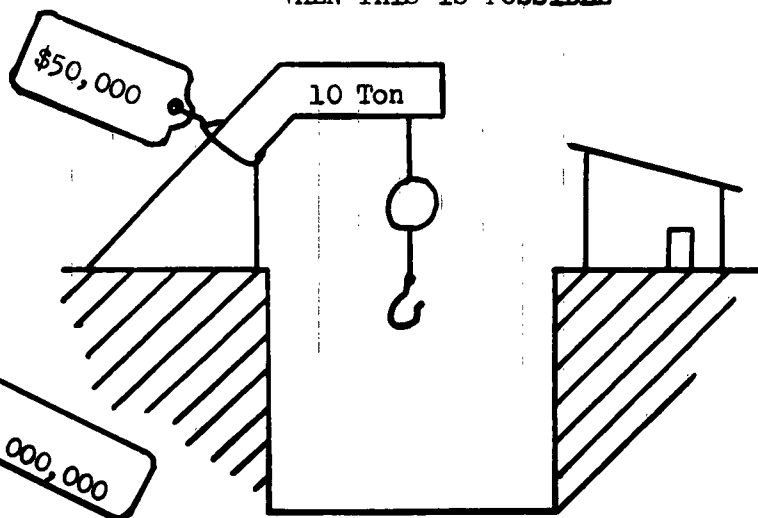
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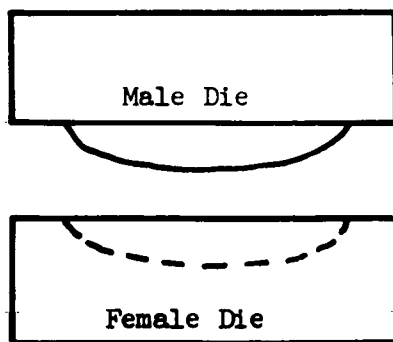
WHY THIS?



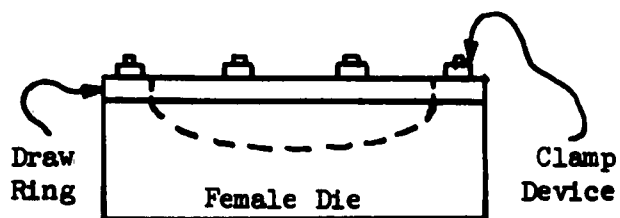
WHEN THIS IS POSSIBLE



WHY THIS?



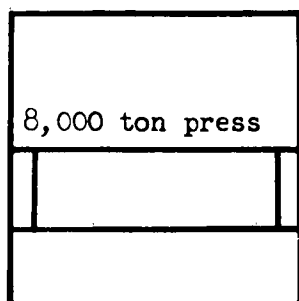
WHEN THIS CAN BE LESS COSTLY



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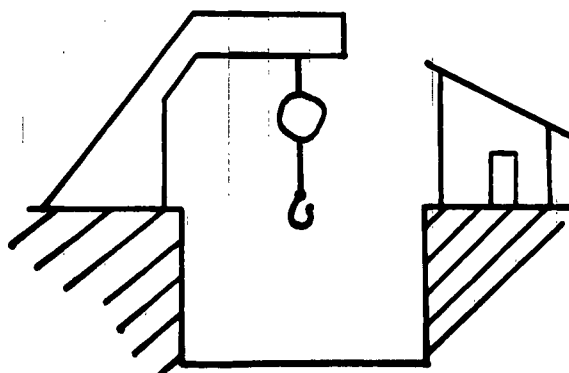
WHY THIS?

2 years lead time



WHEN THIS CAN SAVE LIVES

6 months lead time



SUMMARY

This publication is primarily concerned with the explosive forming activity in industry and the U. S. Army. It is the intent of this publication to familiarize U. S. Army Materiel Command personnel with the applications and limitations of the explosive forming method.

The explosive forming method can be most effectively utilized where any of the following conditions exist:

1. Common or unusual configurations which are difficult or impossible to form by conventional means can be formed in one piece instead of costly welded subassemblies.
2. Where the tolerances required cannot be obtained by conventional methods.
3. Where many conventional forming operations can be combined into a single explosive forming operation. For example, a part can be formed, embossed, and holes pierced in one shot.

The advantages of explosive forming are:

1. There is virtually no limit to the size part that can be formed.
2. Any thickness of common or high strength metal can be formed.
3. The capital investment is low because expensive machinery is not required.
4. Tooling is cheaper than conventional tooling for small production quantities or large parts because only a female die half is required.
5. Surface finish is better as compared to conventionally formed parts.
6. Explosives are a low cost source of unlimited forming pressures.
7. Close tolerances can be obtained on virtually any size part.
8. Heat treatment operations for some parts and/or materials are reduced or even eliminated.
9. Greater uniformity is achieved than is possible by conventional forming methods.

10. Mobilization lead time is less than conventional and most nonconventional forming methods.

11. Part may be formed with variable section thickness.

The bibliography of this publication lists 164 articles and recommends those which are the most useful.

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1. Purpose: To familiarize personnel in the U. S. Army Materiel Command who are engaged in contractual, procurement, and design activities with the basic concepts, industrial capacity, and applications of the explosive (chemical) method of forming materials.

2. Scope: This review will be primarily concerned with the high explosive method of forming, as the low explosive (shotgun shells, etc.) method of forming is being replaced--for the most part--by the electrical discharge and magnetic forming methods.

3. Discussion:

a. History: Prior to 1900, German (1), American (2), and British (1) engineers were awarded patents for explosive forming methods, but the technique lay dormant until about 1954 when interest in it revived. The advent of the missile age with its large and complex parts, high strength materials, close tolerances, and relatively low production volumes appears to have provided the greatest impetus to the method, although the Moore Co. (3) of Marceline, Missouri, was one of the first to recognize the benefits of this method for commercial production operations. Since the "rediscovery" of this method, it has passed through a period of much overstatement and failure, but today it is beginning to be re-established as a useful method of production.

b. General Description: The process is generally set up as shown in Figure One, when a liquid transfer media is used. The process equipment is simple, consisting mainly of a liquid containing tank, female die, vacuum pump, and an explosive with some means of detonation. Not shown in Figure One is a lifting device needed to handle the die and material. The liquid serves as a media for the transferral of the shock waves (which supply the major portion of the energy (4)) and gas pressure generated by the detonation of the explosive. A vacuum pump is required to evacuate the die cavity to reduce forming resistance and to eliminate the burning of the die side of the material and the die. This burning is a result of the excessive temperatures (as high as 10,000°F (8)) generated by the compression of the gas entrapped in the die cavity (4). The writer has encountered cases where users of this process have had to draw a vacuum of 29.5" Hg in order to prevent the auto-ignition of the die lubricant which occurred at higher absolute pressures. This auto-ignition can create springback and dents in the part being formed.

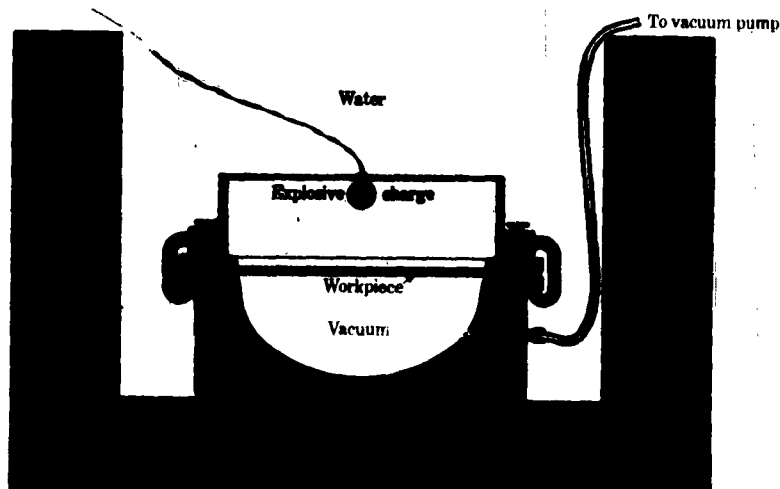


Figure 1. Reprinted from the September, 1961 issue of Fortune Magazine by Special Permission; (C) 1961, Time, Inc.

In other instances, a vent hole in the die is sufficient to prevent this occurrence, particularly in cases where tolerances are not critical and/or the draw is not deep (5).

One of the major problems associated with the vacuum requirement is the need for part-to-die seals. Much work has been done in this area and this problem can now be largely overcome (6) (7).

The selection of the proper explosive depends upon the particular application being considered. Some of the explosives used for explosive forming include PETN, RDX, TNT, nitroglycerine, 30% ammonia Gel, cyclonite (5), aerex (patented by Aerojet-General), and Nitroguanidine (10) with the latter explosive used almost exclusively in the direct contact method of explosive forming. These explosives have been used in the form of a powder, sheets, liquid, cords, pellets, and cylinders, depending upon the needs of the particular application (5). In general, any explosive which is homogeneous and can be handled safely can be used for forming purposes (4).

The media used also depends upon the particular application. Table One illustrates this fact (11). For example, a high temperature media is used to form tungsten (12).

ENERGY TRANSFER MEDIA FOR EXPLOSIVE FORMING

FORMING MEDIA	TEMPERATURE (°F)					
	R.T.	R.T. - 500	500 - 1000	1000 - 1500	1500 - 2000	2000+
WATER	X					
RUBBER	X	X				
HYDRAULIC OILS	X	X	X			
GLASS				X	X	X
SAND	X	X	X			
MOLTEN SALTS			X	X		
MOLTEN ALLOYS					X	X
AIR	X	X	X	X	X	X
INERT GAS	X	X	X	X	X	X

Table 1. Reprinted by special permission from Research and Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, from Report No. ASD-TDR-63-7-871, dated July 1963.

The net pressure exerted on the part by means of a standoff charge can be varied from several thousand to several hundred thousand pounds per square inch by changing one or more of the following process variables:

1. Evacuation of the die cavity (5)
2. Type of charge
3. Weight of charge
4. Charge geometry

5. Stand-off distance
6. Transfer medium
7. Pressure confinement (13)

In addition to the above variables, the actual application setup will depend upon the material to be formed, its strength and thickness, the part configuration, duration and rate of pressure application, and die design (5). The manner in which the above variables effect material forming is demonstrated by the contention that the pressure exerted on the part varies inversely with stand-off distance (14) and directly with the one-third power of the weight of the explosive charge (15), when using a water media. The multiplicity of variables involved in any given application has created much confusion regarding the usage of the method. Obviously, the values of these variables for a steel part would not apply to an aluminum part because of the differences in the properties of the materials (13).

A few of the other explosive forming techniques used are depicted by Figures Two, Three, Four, Five, and Six below.

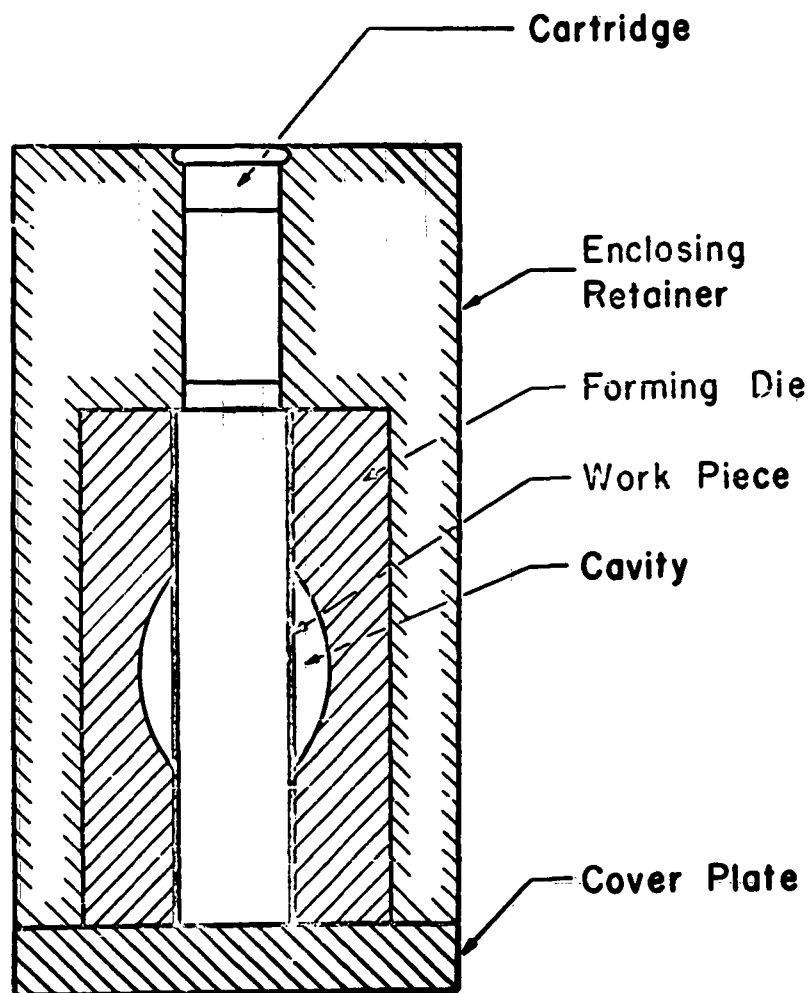


Figure 2. Courtesy of U. S. Naval Ordnance Test Station

Figure Two (16) depicts the low explosive closed split die technique which has been used primarily for small part bulging operations.

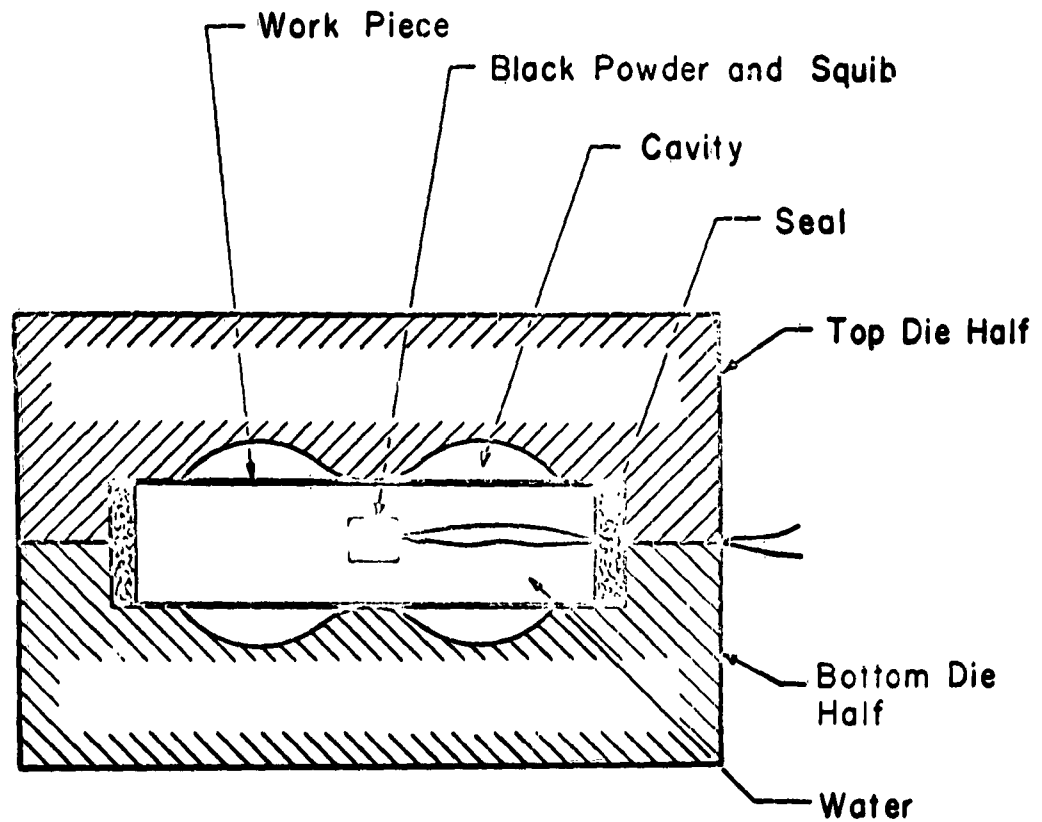


Figure 3. Courtesy of U. S. Naval Ordnance Test Station

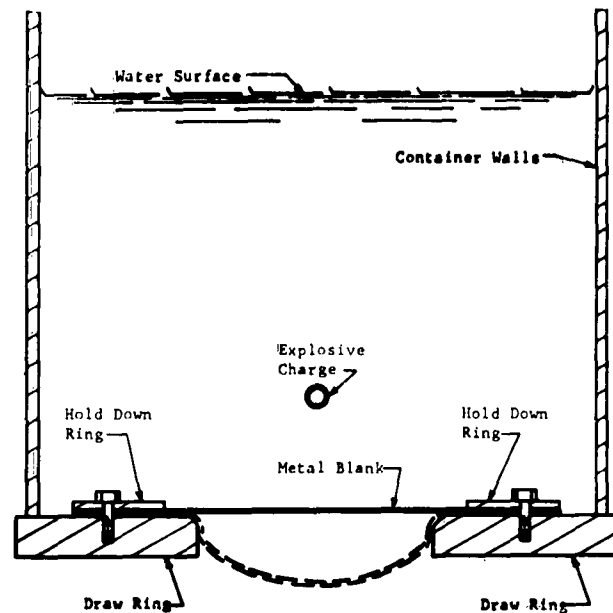


Figure 4. Courtesy of Permagon Press

Figure Four (18) illustrates the use of an explosive forming technique in which certain parts can be made without the use of a die (18). Although its usage is not widespread, it is, no doubt, of great economic value in the forming of some part configurations.

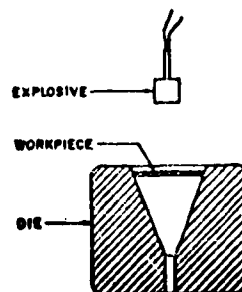


Figure 5. Courtesy of CARDE

Figure Five (18) above represents a technique that appears to have been developed by the Canadian Armament Research and Development Establishment who have since discontinued all explosive forming research due to the press of other duties (19). However, the Explosiform Corp. of Park Forest, Illinois has continued research on this method for hemispherical shapes (20).

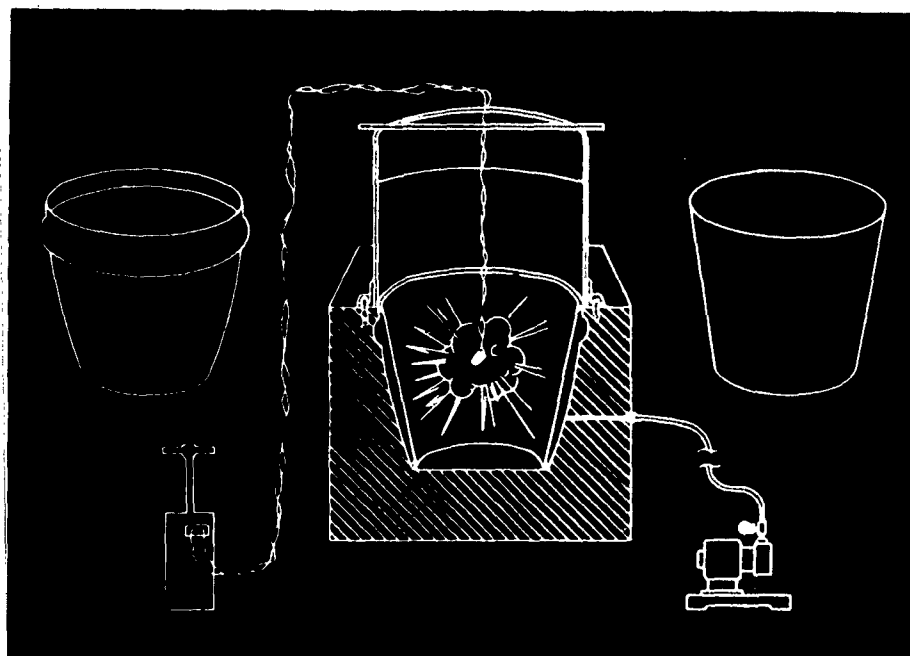


Figure 6. Reprinted by special permission from THE INDUSTRIAL PRESS from the article "Ryan's Split-Second Explosive Forming" by Charles C. Herb as published in the July 1959 issue of MACHINERY.
C 1959

Figure Six (23) above is an example of the use of high explosives in bulging a part from a preform utilizing a split die and a water media. This method has found widespread application.

Other variations, not shown here, have also been developed (Martin Company's plug cushion and sandwiching techniques) to solve specific forming problems (21).

A general outline of the explosive forming operation sequence is as follows (22):

1. Clean, then lubricate die.
2. Install blank.
3. Draw vacuum (not required for dieless "or vented die" techniques).
4. Position charge.
5. Lower die into liquid media (not required for open air or closed die technique).

6. Detonate charge.

7. Pull die out of liquid media (if used), and inspect results.

As noted above, some of these operations can be eliminated depending upon the particular explosive forming technique being implemented.

One of the first reactions to explosive forming is that its use would create a severe sound level problem. This is not necessarily true if the explosive is detonated well below the surface of the water media. A report made by Lockheed to the U. S. Air Force states that "The sound level generated during an explosive forming cycle when a heavy charge is detonated under water in the 13-foot diameter forming tank, with the air curtain functioning, will not approach that of standard drop hammer equipment" (6). Open-air shots, however, are excessively noisy.

The "air curtain" mentioned above is a technique used to attenuate the explosive shock effects on the walls of the liquid container of permanent facilities and is created by means of a perforated air hose which is coiled around and away from the die and part (6).

c. Tooling: The proper die material depends upon such variables as the part configuration, quantity of parts to be produced, tolerances required, material to be formed, and the quantity of explosive and standoff distance used (6). Table Two below lists the general recommendations for die materials on drawn parts as determined in a study for the U. S. Air Force (6). This same report recommends cast steel for dies used on expanding and/or sizing operations (6).

Total Quantity of Parts	Qty of Material to be formed ($\times 10^3$)		
	10 - 30	31 - 60	61 and up
1 - 10	Epoxy	Kirksite	Cast Steel
10 - 20	Kirksite	Kirksite	Cast Steel
20 - 100	Kirksite	Cast Steel	Cast Steel

Table 2. Courtesy of U. S. Air Force

MATERIALS FOR ECONOMICAL FORMING DIES

QUANTITY OF PARTS	YIELD STRENGTH OF MATERIAL TO BE FORMED (K.S.I.)			
	10-25	25-75	75-150	150 +
1-10	A	B	C	D
10-100	B	C	D	D
100-500	C	D	D	E
500-UP	D	D	E	E

A - PLASTIC AND PLASTIC FACED
 B - KIRKSITE
 C - BOILER PLATE OR CAST STEEL
 D - ALLOY STEEL (4130, 4340, ETC.)
 E - TOOL STEEL (H-11)

Table 3. Reprinted by special permission from Research and Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, from Report No. ASD-TDR-63-7-871, dated July 1963.

Table Three (11) above is another set of general recommendations arising from another study made for the U. S. Air Force.

Other general guidelines drawn by Martin-Denver are as follows (24):

Ductile Cast Iron: Good for high pressures and frequent use. Excellent for aluminum alloys.

Kirksite: Should be used for small number of parts requiring low explosive pressures.

Concrete: Restricted to a small number of parts and used mainly for large parts due to cost savings in die construction.

Fiberglas and Concrete: Restricted to a small number of parts requiring low pressures. Used mainly for large parts for economic reasons. Fiberglas will separate from concrete with repeated usage.

Epoxy and Concrete: Similar to fiberglas and concrete.

Fiberglas and Kirksite: Also restricted to a small number of parts requiring low explosive pressures.

Ryan Aeronautical Company has expressed the following opinions regarding die materials (25):

1. There is no substitute for steel (wrought or cast) for long part runs. Mild steel is useable in many cases.

2. Kirksite will probably do an excellent job on limited production of light gauge aluminum alloy parts.

3. Epoxy will do a fair job if only one or two parts are required.

4. Concrete, plaster, fiberglass, etc., will produce nothing but trouble.

DuPont (15) advanced the advice that "low strength" dies should only be used for short runs and parts not requiring critical tolerances. He also cited DuPont's poor experience with cast materials because of casting defects and stated that wrought materials should be used. The general design parameter which he felt could be applied to die design is that the die material should have a higher yield strength than the part being formed.

Additional comments regarding die design include the use of pressure plates to eliminate wrinkles (14), the lack of a need for "stage" dies for explosive forming (26), the possibility of breaking dies by poor design (27), and the need for die face finishes of 60 microinch for as-formed finished parts (28).

Specific examples of die material usage which have been cited are: 150 nosecones produced on epoxy-faced die without wear and other plastic usage examples (29), steel dies cast of ASTM-A-216 which were not porous and did not become oversized (30), failure of fiberglass-faced die in forming aluminum bulkheads (31), and the use of a combination steel and kirkite die to produce 30 bulged parts to a ± 0.030 " tolerance on the diameter (22).

Dies for sizing operations are more critical in a design sense because more of the explosive energy is transferred to the die. This is due to the low deformation of the part and the intimate contact of the part with the die. These two conditions cause more of the energy to be transferred to the die with the resultant higher possibility of die breakage or distortion.

In summary, the success of the die materials used will depend a great deal upon the general explosive forming knowledge of the personnel conducting the operations, since a die is designed for an expected pressure and may be broken or unnecessarily distorted if the actual pressure exerted during forming operations is greater. Further references regarding tooling are cited in the "additional literature" section of the bibliography.

d. Tolerance Capabilities: As stated in the tooling section, the tolerance obtainable by explosive forming is a function of the die design, vacuum drawn, part size and configuration, explosive size and standoff distance, etc. One innovation used to improve tolerances is the placement of a rubber or plastic mat on top of the part to increase the duration of the application of force (32).

In general, there are not many instances where the explosive forming technique cannot equal--or better--tolerances obtainable with conventional forming methods (32). Tolerances of $\pm .001$ " have been reported but, normally, working tolerances are on the order of $\pm .010$ " (32). Material thickness tolerances reportedly can be held to $\pm .004$ " (33). One company has indicated tolerance capabilities as shown in Table Four below. It can be readily seen that the size and shape of the part affects the tolerance capability of this technique.

GENERAL TOLERANCES				
	Part Maximum Dimension-Inches			
	<u>Up to 12.0</u>	<u>13.0 to 24.0</u>	<u>25.0 to 120.0</u>	<u>1200 to 360.0</u>
Mold Line Location	$\pm .002$ "	$\pm .004$ "	.010"	.030"
Radius of Bulge on Sized Cylinder	$\pm .001$	$\pm .002$	$\pm .008$	$\pm .015$
Radius of Dome on Hemispherical Shape	$\pm .002$	$\pm .004$	$\pm .010$	$\pm .020$
General Sh. Met. Tol. For Complex Shapes	$\pm .005$	$\pm .015$	$\pm .030$	$\pm .060$

Table 4. Courtesy of Lockheed-California Company

TOLERANCES OBTAINABLE WITH
EXPLOSIVE FORMING IN THE
FABRICATION OF MISSILE DOMES

DIMENSION	TOLERANCE	
	Normal	Possible
Diameter	$\pm .10$ "	$\pm .005$ "
Contour	$\pm .020$ "	$\pm .010$ "
Thickness	$\pm .004$ "*	$\pm .002$ "*

*Surface Preparation Required

Table 5. Courtesy of JANAF-ARPA-NASA

Another company's experience with tolerances on AMS6434 54" diameter missile domes which were .125" thick and had an elliptical cross section of eccentricity 1.6 is given in Table Five. As can be seen from this Table, part surface preparation is required to obtain the tight tolerances on material thickness.

As an indication of the tolerance capabilities of this technique, some of the specific part tolerances obtained have been: 31 out of 37 U. S. Army missile skins were accepted on the basis of a $\pm .01$ " tolerance on contour (28), a "hub cap" type part formed to $\pm .007$ " on contour (25), a radar reflector formed to $\pm .01$ " tolerance on the contour (25), 70" diameter 5086 aluminum hemispheres held to $\pm .008$ " tolerance (34) and 42" diameter missile domes held to $\pm .02$ " on the diameter, thickness to $\pm .01$ " and contour tolerance held to $\pm .025$ ". One manufacturer has recommended that the aluminum hemispheres it produces by explosive forming should have a minimum tolerance of $\pm .004$ " on wall thickness and $\pm .002$ " on stainless steel hemisphere wall thickness (35).

In summary, it appears that this forming method would lend itself to formed parts which must be joined by welding since the relatively close tolerance capability would prevent some of the current mismatching problems encountered by parts formed conventionally and welded. This method would become even more applicable to this type of operation if the parts are relatively large.

e. Material Reaction and Mechanical Properties: Much controversy has arisen over the years in regard to the manner in which materials react during forming and a material's reaction to forming. This controversy is a direct result of individuals dealing in generalities. Normally, discrepancies in material data can be traced to different test or measurement methods and general statements which are not specifically associated with a particular material.

An example of the measurement problem is the effect of the critical impact velocity on the amount the material can be deformed. The critical impact velocity is that velocity of metal movement beyond which the material becomes brittle and exhibits decreased formability (13). Martin (24) cites a Ling-Temco-Vought study as stating that even within a given material, elongation becomes a function of the velocity at which forming takes place. Low-to-moderate forming speeds cause elongation to be unchanged from values resulting from static tests. Forming speeds above the material's critical-impact-velocity cause a rapid decline in the highest elongation possible, and a short range of forming velocities just below the critical-impact-velocity result in elongations appreciably greater than the static values. The main difficulty here is establishing the various forming velocity ranges for a given material so as to maximize the elongation by varying process parameters. Accordingly, the velocity of forming or the specific parameters used must be stated for the corresponding elongation being cited before the elongation results can be completely useful to other users.

TABLE 6. Critical Impact Velocities and Associated
Critical Normal Fracture Stresses
(After Rinehart and Pearson, Ref. 8)

Material	Critical Impact Velocity, (ft/sec)	Associated Normal Fracture Stress, (psi)
24S-T4 Aluminum	202	140,000
Brass	216	310,000
Copper	264	410,000
1020 Steel	84	160,000
4130 Steel	235	440,000

Table 6. Courtesy of U. S. Naval Ordnance Test Station

Table Six above cites the critical impact velocities for a few materials.

Another point of contention which most users agree upon now is that the material behaves plastically when high forming velocities are applied (13).

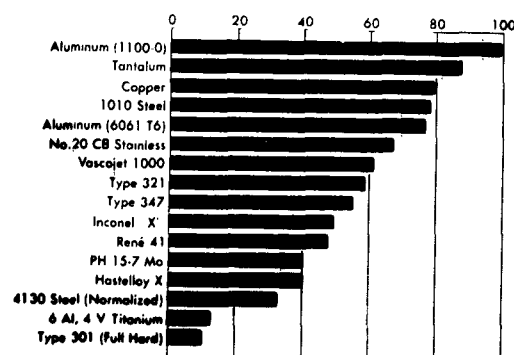
Requirements for larger and larger parts have resulted in the need for welded blanks because raw material of any type is limited in size. A general rule for handling a situation of this type is to place the weld in such a position that the required plastic strain is held to a minimum. This is the result of the decreased ductility of the weld zone (50).

A few specifics on material reaction to forming which have been cited are: high manganese and high nickel steel alloys experienced increased ductility when strained rapidly (1), 18-8 stainless steel demonstrating reduced corrosion resistance (36), domes of 5086 aluminum maintaining a yield strength of 30,000 psi (34), domes of AM355 stainless steel having a yield strength of 230,000 psi (34), increased formability of four percent for A-286 and 77 percent for 17-7 PH stainless (37), titanium alloys requiring elevated temperatures to facilitate formability (38), austenitic and precipitation hardening stainless steels exhibiting increased elongation (38), aluminum alloys readily formed (38), 5086-H34 Diamond Pyramid Hardness values increasing from 93 DPH to 105 DPH (39), varying degrees of cold work experienced by zircaloy-2 (40), and one piece explosively formed 2014 aluminum dome exceeding welded assembly dome strength (41).

Table Eight below lists the relative formability of alloys by explosives. These formability figures give some indication of the relative size of the explosive charge required to form a part when different alloys are used.

Table 8

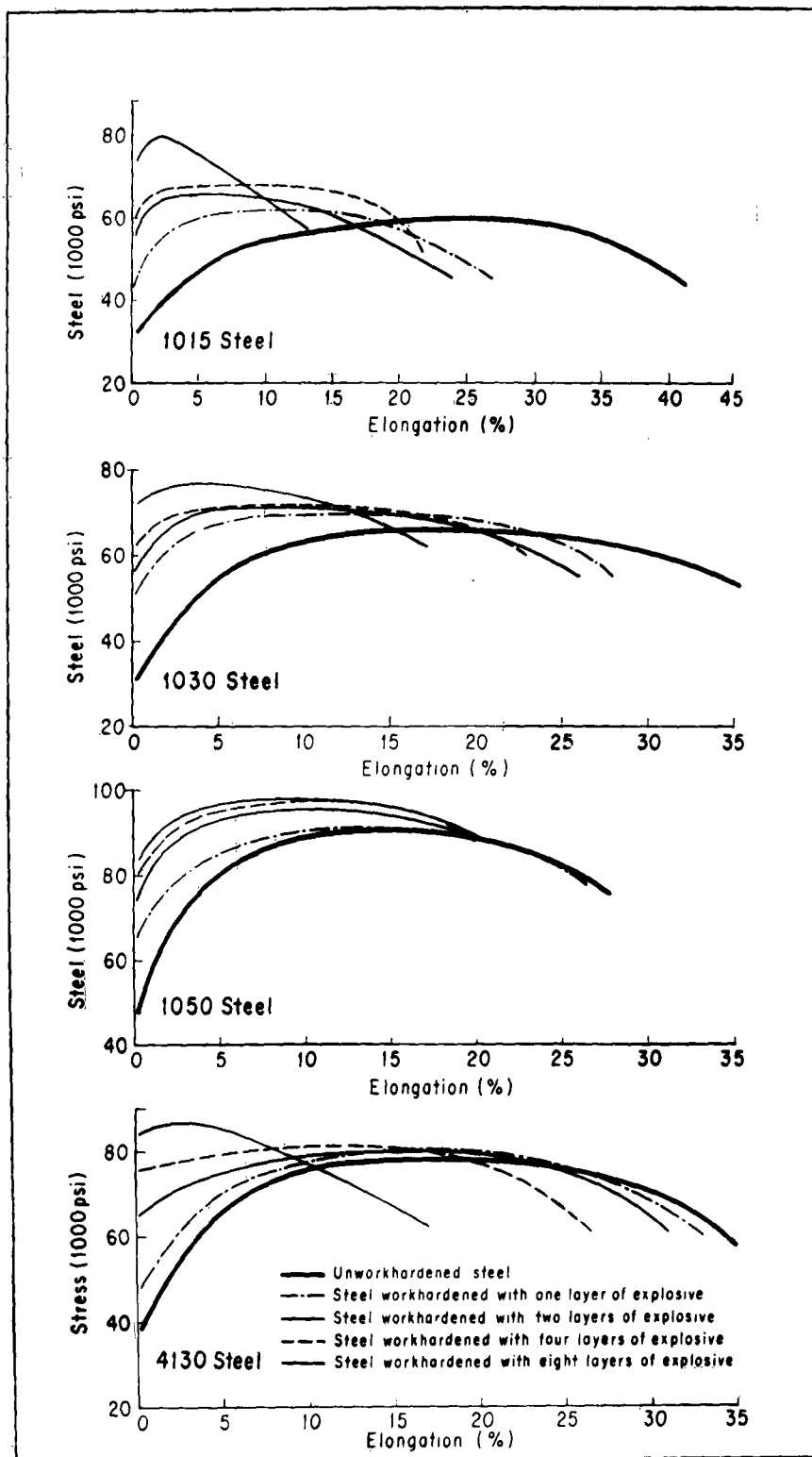
Reprinted by special permission from AMERICAN SOCIETY FOR METALS from the article "How to Design for Explosive Forming" by Vernon H. Monteil as published in the August 1961 issue of METAL PROGRESS. © 1961



<u>Metal or alloy</u>	<u>K_m</u>
Nickel.	1.0
Stainless steel	1.1
Titanium	1.5
Plain carbon steels	2.3
Aluminum	2.5

Table 9. Courtesy of ASME

Table Nine above is the result of tests conducted by an early explosive forming experimenting firm. K_m here indicates the amount of elongation experienced by a particular metal with explosive forming as compared to conventional methods. The medium used was water and the part temperature was ambient. This data must be used carefully if credence is given to Ling-Temco-Vought's critical-impact-velocity proposition cited earlier.



Workhardening effect of various size charges on steel plates

Figure 7. Reprinted by special permission from McGRAW-HILL PUBLISHING COMPANY, INC., from the article "What Happens to Explosively Worked Materials" by John Pearson and George A. Hayes as published in the 16 October 1961 issue of AMERICAN MACHINIST/METALWORKING MANUFACTURING. C 1961

The above figure illustrates the results of a study conducted by the Naval Ordnance Test Station at China Lake.

Note Strength of Forged Door

ALLOY 7075	YIELD STRENGTH, psi	TENSILE STRENGTH, psi	ELONGATION, pct
As forged (ambient)	45,200	51,600	4.0
As forged (at 500°F)	28,500	37,100	10.0
After heat treat (ambient)	73,000	81,200	12.0
After heat treat (500°F)	70,300	78,600	10.0

NOTE: Parts were erroneously heat treated for alloy 2014.

Table 10. Reprinted by special permission from CHILTON COMPANY from the article "Explosive Forms Aluminum Door" as published in the 22 September 1960 issue of THE IRON AGE.
C 1960

Table Ten illustrates the results of explosive forming a 7075-0 aluminum door. It should be noted that the physical properties cited are better than those which can be obtained by conventional forming.

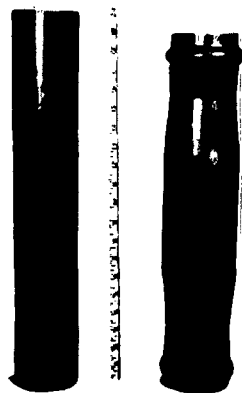
The following pictures are of parts formed by low explosive, closed die methods. The corporation operational division which formed these parts is no longer in operation. They are presented here only to indicate the property changes experienced by the materials used in these parts.

In summary, the mechanical property changes resulting from explosive forming a material are a function of the particular material and the part being formed. This is no different from any other forming process. While the final properties achieved as a result of forming explosively may be different from those achieved by forming conventionally, no sweeping general statement can be made which will not encounter exceptions.

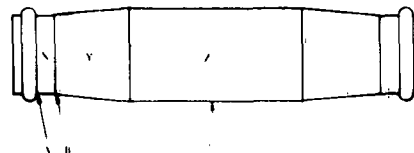
The amount of elongation experienced by a material is considerably more difficult to determine and, therefore, it is even more difficult to make generalized statements about.

SOUND SUPPRESSOR TUBE (SMALL) FOR BOEING 707 (120)

Material: Type 321 Stainless Steel



Formed Part



Dimension Specifications

- A $3.55 \pm .010$ " I.D.
- B $3.41 \pm .010$ " I.D.
- C $4.00 \pm .030$ " O.D.

Preformed Part: Formed by (1) shearing blank, (2) rolling preform, (3) welding preform, and (4) planishing weld

$3.46 \pm .030$ " O. D.
 $19.875 \pm .125$ " Length
 .025" Gage Thickness

Dimensions After Forming (From 25 Parts)

<i>Location</i>	<i>Average</i>	<i>Maximum</i>	<i>Minimum</i>
A (I. D.)	3.553"	3.560"	3.544"
B (I. D.)	3.418	3.423	3.410
C (O. D.)	3.984	3.990	3.978

Annealed Condition

Tensile Strength: 84,500 to 86,000 psi

Yield Strength: 26,000 to 27,500 psi

Elongation in 2": 46 to 48%

Rockwell "B" Hardness: 71 to 73

Gage in Area of Maximum Bulging

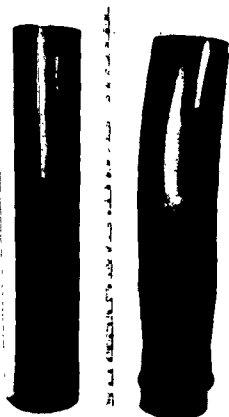
<i>Average</i>	<i>Maximum</i>	<i>Minimum</i>
.021"	.023"	.017"

Properties

<i>Area</i>	<i>Tensile Strength</i>	<i>Yield Strength</i>	<i>Percent Elongation</i>	<i>Rockwell "B" Hardness</i>
X	95,000 psi	46,000 psi	43	86
Y	99,000	56,000	37	91
Z	110,000	73,000	25	96

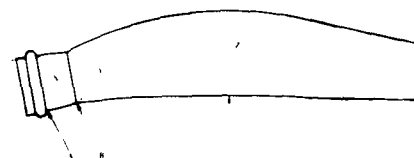
Figure 8. Reprinted by special permission from OLIN MATHIESON CHEMICAL CORPORATION, WINCHESTER-WESTERN DIVISION, from their brochure titled, "SUPER SPEED Metal Forming".

SOUND SUPPRESSOR TUBE (LARGE) FOR BOEING 707 (120)



Material: Type 321 Stainless Steel

Formed Part



Dimension Specifications

A $5.62 \pm .010$ " I.D.
 B $5.41 \pm .010$ " I.D.
 C $6.25 \pm .030$ " O.D.

Preformed Part: Formed by (1) shearing blank,
 (2) rolling preform, (3) welding perform, and
 (4) planishing weld

$5.25 \pm .030$ " O. D.
 $31.00 \pm .125$ " Length
 $.030$ " Gage Thickness

Dimensions After Forming (From 25 Parts)

<i>Location</i>	<i>Average</i>	<i>Maximum</i>	<i>Minimum</i>
A (I. D.)	5.613"	5.622"	5.606"
B (I. D.)	5.407	5.422	5.399
C (O. D.)	6.227	6.260	6.200

Annealed Condition

Tensile Strength: 90,500 to 92,500 psi

Yield Strength: 30,500 to 32,500 psi

Elongation in 2": 46.5 to 48%

Rockwell B" Hardness: 78 to 79

Gage in Area of Maximum Bulging

<i>Average</i>	<i>Maximum</i>	<i>Minimum</i>
.028"	.029"	.025"

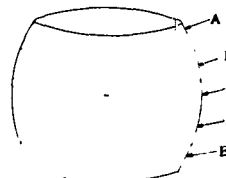
Properties

<i>Area</i>	<i>Tensile Strength</i>	<i>Yield Strength</i>	<i>Percent Elongation</i>	<i>Rockwell "B" Hardness</i>
X	95,500 psi	48,700 psi	37.8	86
Y	113,500	78,800	23.0	98
Z	111,900	79,900	19.0	97

Figure 9. Reprinted by special permission from OLIN MATHIESON CHEMICAL CORPORATION, WINCHESTER-WESTERN DIVISION, from their brochure titled, "SUPER SPEED Metal Forming".

EXPERIMENTAL HOLLOW CYLINDER

Material: 1020 Steel

Unformed Cylinder**Formed Cylinder****Average Dimensions After Forming**

Location	O. D.
A & A'	7.270"
B & B'	7.969"
C	8.385"

**Unformed Hollow Cylinder
Contained A Weld.**

Average O. D.	6.656"
Length	6.000"
Wall Thickness	.296"

Wall Thinning

Location	Average Gage Before	Average Gage After	Thinning
A & A'	.296"	.278"	.018"
B & B'	.296"	.258"	.038"
C	.296"	.246"	.050"

Length	
Average Length Before	6.00"
Average Length After	5.42"
Average Length Decrease	0.58"

Metallurgical Properties

Location	Tensile Strength	Yield Strength	Percent Elongation	Rockwell "B" Hardness
ORIGINAL	55,000 psi	32,000 psi	29.0	62
A & A'	59,000	38,500	23.5	67
B & B'	62,500	44,500	19.0	73
C	71,000	56,500	9.0	84

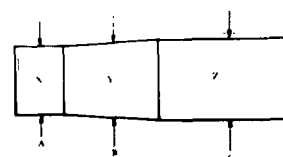
Figure 10. Reprinted by special permission from OLIN MATHIESON CHEMICAL CORPORATION, WINCHESTER-WESTERN DIVISION, from their brochure titled, "SUPER SPEED Metal Forming".

EXPERIMENTAL SOUND SUPPRESSOR

Material: 4130 Steel



Formed Part



Preformed Part: Formed by (1) shearing blank,
(2) rolling preform, (3) welding preform and
(4) planishing weld

3.450" - .040" O. D.
11.170" - .050" Length
.025 Wall Thickness

Tensile Strength: 72,300 psi
Yield Strength: 43,800 psi
Elongation in 2": 24.5%
Rockwell "B" Hardness: 75.3

	Length
Average Length Preform	11.147"
Average Length Formed Part	10.652"
Average Length Decrease	0.495"

Dimension Specifications

A 3.460" $\pm$.010" O.D.
B 3.752" $\pm$.010" O.D.
C 4.044" $\pm$.030" O.D.

Wall Thinning

Area	Average Gage Before	Average Gage After	Thinning
X	.025"	.023"	.002"
Y	.025"	.021"	.004"
Z	.025"	.020"	.005"

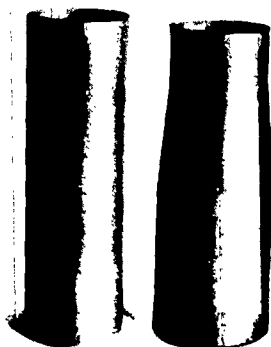
Metallurgical Properties

Area	Tensile Strength	Yield Strength	Percent Elongation	Rockwell "B" Hardness
X	69,250 psi	43,700 psi	23.0	75.0
Y	76,450	59,700	13.0	84.6
Z	83,600	74,850	8.0	98.1

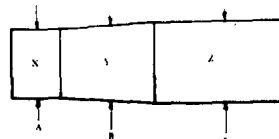
Figure 11. Reprinted by special permission from OLIN MATHIESON CHEMICAL CORPORATION, WINCHESTER-WESTERN DIVISION, from their brochure titled, "SUPER SPEED Metal Forming".

EXPERIMENTAL SOUND SUPPRESSOR

Material: AM 350 Stainless Steel



Formed Part



Dimension Specifications

A 3.460" $\pm$.010" O.D.

B 3.752" $\pm$.010" O.D.

C 4.044" $\pm$.030" O.D.

Preformed Part: Formed by (1) shearing blank, (2) rolling preform, (3) welding preform, and (4) planishing weld

3.450" - 040" O D.

11.170" - .050" Length

.0158" Wall Thickness

Tensile Strength: 131,000 psi

Yield Strength: 58,400 psi

Elongation in 2": 21.0%

Rockwell "B" Hardness: 96.0

Wall Thinning

Area	Average Gage Before	Average Gage After	Thinning
X	.0158"	.0135"	.0023"
Y	.0158"	.0130"	.0028"
Z	.0158"	.0125"	.0033"

	Length
Average Length Preform	11.1385"
Average Length Formed	10.6878"
Average Length Decrease	.4507"

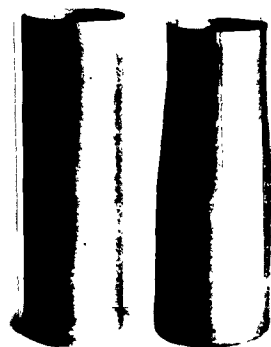
Metallurgical Properties

Area	Tensile Strength	Yield Strength	Percent Elongation	Rockwell "B" Hardness
X	132,300 psi	56,600 psi	20.9	94.5
Y	163,800	71,750	16.1	99.3
Z	178,000	96,400	10.9	106.0

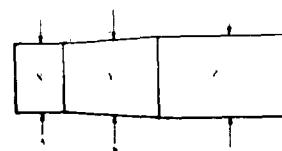
Figure 12. Reprinted by special permission from OLIN MATHIESON CHEMICAL CORPORATION, WINCHESTER-WESTERN DIVISION, from their brochure titled, "SUPER SPEED Metal Forming".

EXPERIMENTAL SOUND SUPPRESSOR

Material: Comm. Pure Titanium



Formed Part



Dimension Specifications

A $3.460'' \pm .010''$ O.D.
 B $3.752'' \pm .010''$ O.D.
 C $4.044'' \pm .030''$ O.D.

Preparation of Preform: Formed by (1) shearing blank, (2) rolling preform, (3) welding preform and (4) planishing weld

$3.450'' - .040''$ O. D.
 $11.170'' - .050''$ Length
 $.023''$ Wall Thickness

Tensile Strength: 79,800 psi
Yield Strength: 48,500 psi
Percent Elongation in 2": 24.75
Rockwell "B" Hardness: 88

Length
Average Length Preform 11.161"
Average Length Formed Part 10.607"
Average Length Decrease 0.554"

Wall Thinning

Area	Average Gage Before	Average Gage After	Thinning
X	.023"	.0225"	.0005"
Y	.023"	.0212"	.0018"
Z	.023"	.0204"	.0026"

Metallurgical Properties

Area	Tensile Strength	Yield Strength	Percent Elongation	Rockwell "B" Hardness
X	80,100 psi	48,350 psi	24.5	89.0
Y	83,300	59,750	17.5	90.6
Z	88,950	73,350	13.5	94.0

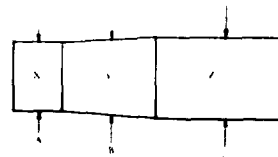
Figure 13. Reprinted by special permission from OLIN MATHIESON CHEMICAL CORPORATION, WINCHESTER-WESTERN DIVISION, from their brochure titled, "SUPER SPEED Metal Forming".

EXPERIMENTAL SOUND SUPPRESSOR

Material: N-155 Stainless Steel



Formed Part



Dimension Specifications

- A 3.460" $\pm$.010" O.D.
- B 3.752" $\pm$.010" O.D.
- C 4.044" $\pm$.030" O.D.

Preparation of Preform: Formed by (1) shearing blank, (2) rolling preform, (3) welding preform and (4) planishing weld

3.450" - .040" O.D.

11.170" - .050" Length

.0175" Wall Thickness

Tensile Strength: 127,900 psi

Yield Strength: 60,800 psi

Elongation in 2": 41.0%

Rockwell "B" Hardness: 94.8

Wall Thinning

Average Area	Average Gage Before	Average Gage After	Thinning
X	.0175"	.016"	.0015"
Y	.0175"	.0147"	.0028"
Z	.0175"	.0135"	.0040"

Length
Average Length Preform 11.405"
Average Length Formed Part 10.6375"
Average Length Decrease 7675"

Metallurgical Properties

Area	Tensile Strength	Yield Strength	Percent Elongation	Rockwell "B" Hardness
X	122,000 psi	56,650 psi	27.0	93
Y	139,000	85,600	19.8	98
Z	139,200	85,400	18.7	99

Figure 14. Reprinted by special permission from OLIN MATHIESON CHEMICAL CORPORATION, WINCHESTER-WESTERN DIVISION, from their brochure titled, "SUPER SPEED Metal Forming".

f. Advantages and Disadvantages:

Advantages which have been cited for this process are:

1. There is virtually no limit to the size part that can be formed (42).
2. Any thickness of common or high strength metal can be formed (42).
3. The capital investment is low because expensive machinery is not required (42).
4. Tooling is cheaper than conventional tooling for small production quantities, or large parts because only a female die half is required (42).
5. Surface finish is better as compared to conventionally formed parts (42).
6. Explosives are a low cost source of unlimited forming pressures (42).
7. Common or unusual configurations which are difficult or impossible to form by conventional means can be formed in one piece instead of costly welded subassemblies (42).
8. Close tolerances can be obtained on virtually any size part (42).
9. Amount of springback is reduced as compared to conventional forming methods, and can be compensated for by die design (42).
10. Many conventional forming operations can be combined into a single high energy forming operation. For example, a part can be formed, embossed, and holes pierced all in one shot (42).
11. Heat treatment operations for some parts and/or materials are reduced or even eliminated (43).
12. Greater part uniformity is achieved than is possible by conventional forming methods (28).
13. Production lead-time is reduced over conventional (44) and some nonconventional methods.
14. Localized stress concentration may be eliminated by uniform force distribution during forming (15).

15. Part may be formed with variable section thickness (2).

Virtually every advantage cited will depend upon the particular part or material being considered for explosive forming. Since this is the case, the above advantages serve the purpose of giving a degree of guidance in selecting parts which are potential explosive forming applications.

The thirteenth advantage above is of particular interest to the U. S. Army because of its mobilization ability.

The disadvantages which have been enumerated are as follows:

1. Production rate is slow (45).
2. Careful handling is required which, in turn, requires specially trained operators (43).
3. Local ordinances may limit the amount of explosives which can be set off (43).
4. The process does not lend itself readily to high temperature forming although high temperature forming has been accomplished (26).

The first disadvantage will, no doubt, be diminished in the near future as several firms are undertaking mechanization studies of this forming method. Such production drags as sealing and clamping will be the first areas studied for the under-liquid explosive forming method. Relatively, the in-air method is capable of producing a greater quantity of parts per unit time since it doesn't require the raising and lowering of the part and die into and out of the liquid medium. This portion of the forming cycle requires approximately 15 minutes depending upon the part and die size, method of explosive suspension, etc.

Disadvantages two and three tend to discourage the development of production capability within the U. S. Army, with disadvantage three playing a predominate role because of production facility locations.

g. Economics: The relative scarcity of cost comparisons of specific parts which have been formed explosively is undoubtedly a result of the widespread use of the technique for parts which cannot be formed by conventional methods. However, there are a few general statements and specific cost comparisons which have been made.

Presently it requires more time to form a part explosively than to form the same part conventionally. However, the use of the explosive forming method becomes more economical as the size and/or complexity of the part becomes greater, and the quantity of parts required becomes smaller (46). This condition is partially due to the relatively lower cost of dies and equipment required for this method (2). Based upon the above conditions, small simple parts requiring large quantities should not be considered for this method (5). Simple is here defined as re-

quiring noncritical tolerance and being producible by conventional means in one piece. However, it should not be construed from the above that explosive forming cannot be used economically for parts requiring considerable quantities as the method has been used to produce as many as 10,000 parts in one production run.

A few specific examples which have been cited are: 6061 aluminum DC-8 nosecones produced at a cost of \$15 each as compared to \$131 each for conventional means (29); 2,000 tube ends squared to close tolerances at a \$10,000 savings (47); and, 42" missile domes formed at a net loss of \$40 each over conventional methods as to achieve better quality (48).

OLIVE OVI

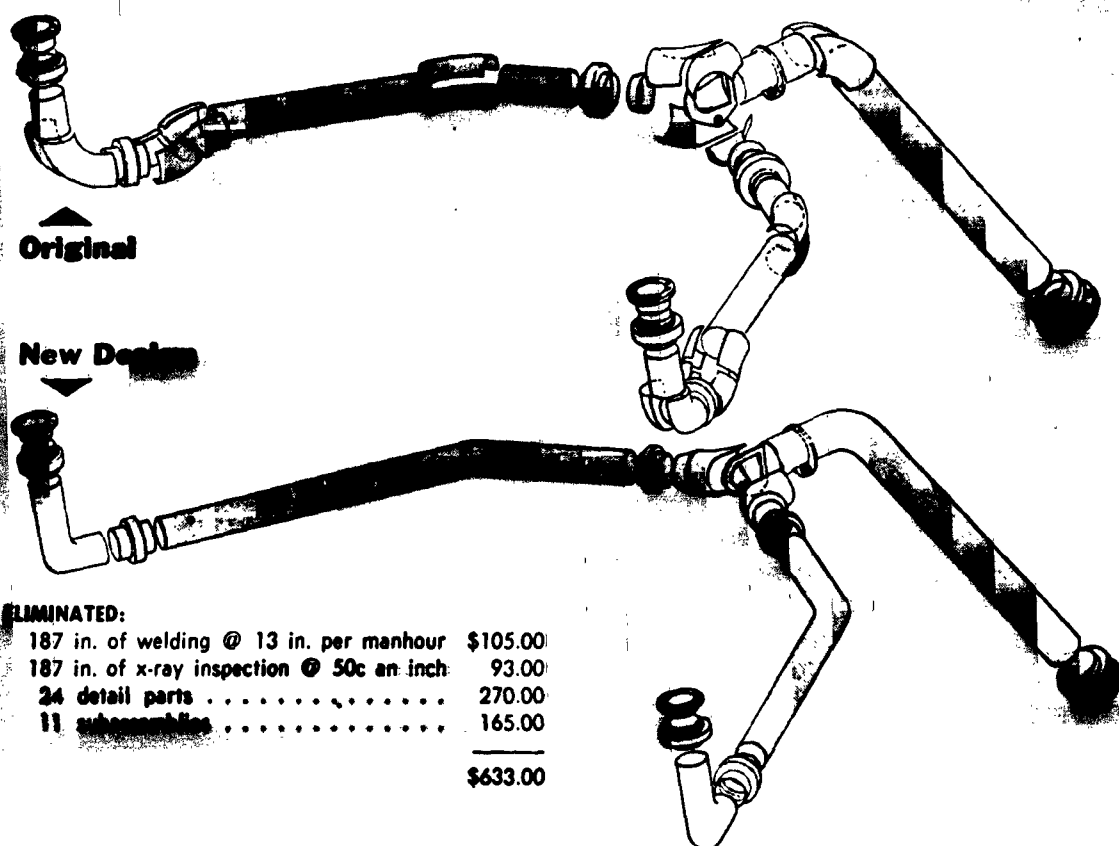


Figure 15. Reprinted by special permission from THE PENTON PUBLISHING COMPANY from the article "Explosive Forming, Tube Bending, Chem Milling Combined to Save \$1276" as published in the 29 July 1962 issue of *AVIATION*.

Figure 15. (cont'd)

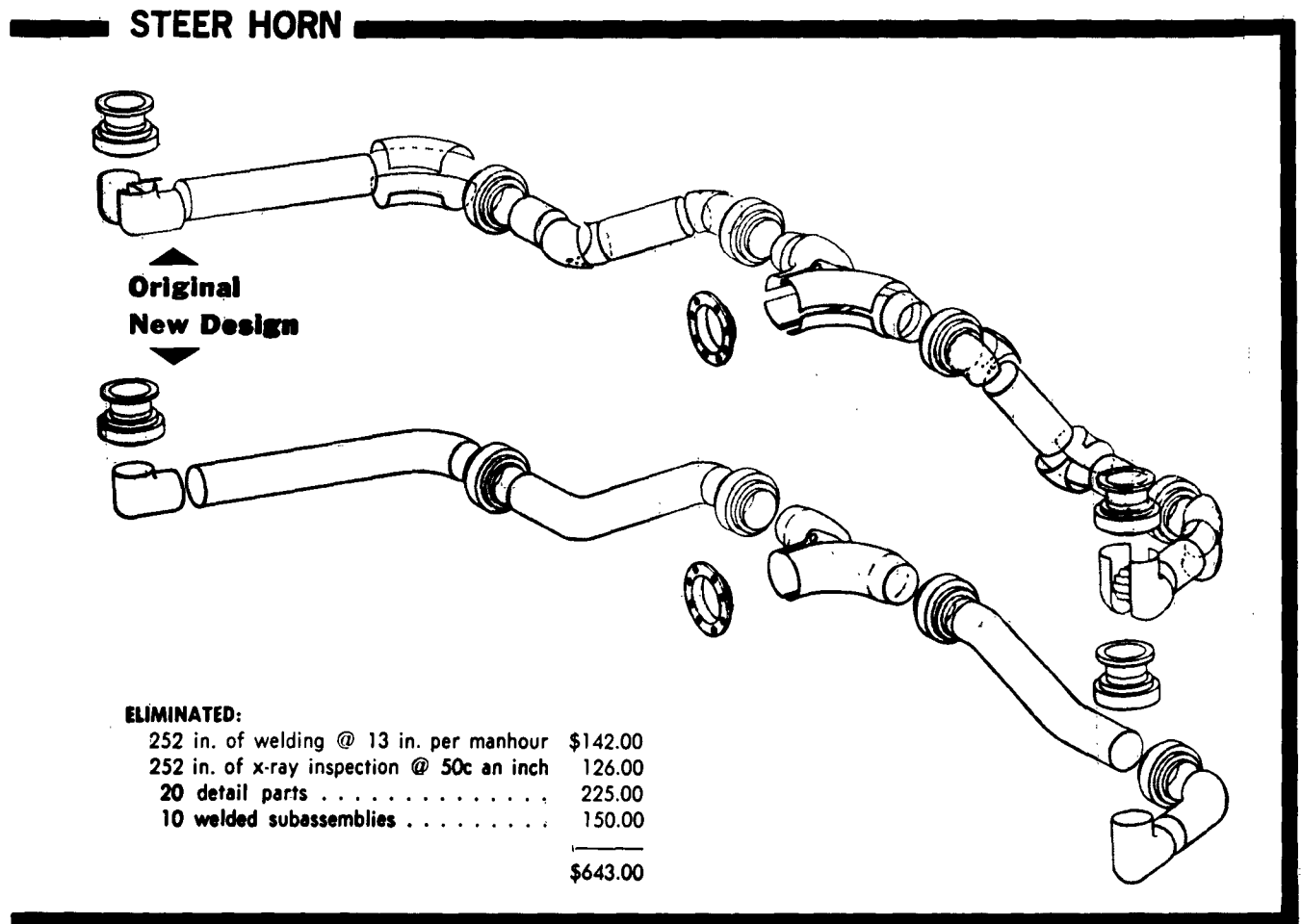


Figure 15 above is an example of cost savings realized by General Dynamics/Astronautics by applying the explosive forming method to piping fabrication.

Table 11 below illustrates the relative cost indexes of producing missile skins by various methods. It is interesting to note the labor index comparison for these methods.

<u>Explosive Forming Operation</u>	<u>Explosive Forming Labor Index</u>
1. Shear (Parallelogram)	1.0
2. Shear (Triangle)	1.0
3. Rout (Radii)	1.6
4. Roll into cone	3.1
5. Weld	4.6
6. Planish Weld	2.2
7. Degrease	1.0
8. Heat Treat	1.6
9. Explosive Form	7.0
10. Heat Treat	1.6
11. Trim to Length	5.3

Material 8.4
Sub-Total 30.0
Total 38.4

<u>Operation</u>	<u>Bulging Labor Index</u>
10. Heat Treat	1.6
11. Final Bulge	5.3
12. Degrease	1.0
13. Heat Treat	1.6
14. Trim to Length	5.3

Material 8.4
Sub-Total 36.1
Total 44.5

<u>Floturn Operation</u>	<u>Floturn Labor Index</u>
1. Hydroform to Preform	.5
2. Hydroform to Preform	.6
3. Floturn Preform	5.8
4. Clean	2.0
5. Anneal	2.0
6. Finish Floturn	11.6
7. Trim	3.0
8. Stabilize	2.0
9. Clean	2.0

Material 20.2
Sub-Total 29.5
Total 49.7

Table 11. Courtesy of Picatinny Arsenal

COMPARISON OF MANUFACTURING COSTS
CONVENTIONAL VS. EXPLOSIVE FORMING (\$ PER PART)

	TOTAL COST		% Increase (+) or Decrease (-) Over Conv. Form.	TOTAL COST		% Increase (+) or Decrease (-) Over Conv. Form.
	100 Qty. Basis			500 Qty. Basis		
	Conventional	Explosive		Conventional	Explosive	
Side Panel-Jet Pot	80.64	89.91 81.29*	+ 11.5% + .8%	35.44	55.03 49.23*	+ 55.3% + 38.9%
Collar - Outlet Housing	6.77	12.99 10.79*	+ 91.9% + 59.4%	2.18	6.12 4.60*	+ 180.7% + 111.0%
Tailpipe Ring	80.63	53.22 50.72*	- 34.0% - 37.1%	38.40	21.68 20.00*	- 43.5% - 47.9%
Pan - Fire Shield	66.91	40.08 36.19*	- 40.1% - 45.9%	22.80	19.19 16.59*	- 15.8% - 27.3%
Bellmouth-Engine Tailpipe	161.47	133.54 128.48*	- 17.3% - 20.4%	57.82	52.75 49.34*	- 8.8% - 14.7%

*Denotes cost of explosive forming as a production operation at CAC.

Table 12. Courtesy of U. S. Air Force

Pictures of the parts tabulated in Table 12 are shown in the pictorial illustrations section. The material used in these parts was AM-350.

Generally, the open-air technique of explosive forming is cheaper, even though this technique utilizes less of the explosive force available. This is due to the fact that the cost of the explosive is a minor portion of the total cost of producing a part, and the lower open-air labor and capital cost more than offsets the increased explosive cost. This technique, however, creates a greater noise problem than the under-liquid technique.

One of the major economic problems confronting explosive forming is the cost of determining the various parameters required to form a particular part. This situation has been partially alleviated by the development of scaling laws. These laws allow the determination of the forming parameters on a scaled-down part. These parameters are then scaled up by the laws to develop the parameters required for the full-size part. Once this has been accomplished, about two or three full-size shots are required to adjust the full-size parameters developed by the scaling laws. Many firms claim this situation to be no worse than the adjustments required for conventional forming and have emphasized their point by offering a fixed price, guaranteed forming type of contract.

Naturally, parts of the same size, configuration, and material as those previously formed by a particular firm do not require further studies. Likewise, a contractor for a particular part should be at least partially selected on the basis of the similarity of the contracted part to parts previously formed by the firm.

The explosive forming technique should be able to compete with other new forming techniques depending again on the part and quantity required. It will probably maintain its capital cost advantage for some time and its mobilization capability will be difficult to overcome.

In summary, as with any technique, the economics for this method must be determined for each particular part. The information supplied in this section can only aid in narrowing the number of alternative methods to consider.

h. Industrial Capabilities and Activity: The intent of this section is to present the capabilities of most of the explosive forming users or researchers within the United States and to illustrate the interest shown by other countries.

AEROJET-GENERAL CORPORATION
 Downey, California
 (Started 1958)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
5083 Al	260" dia (formed)	36 ton jib	10# high
18% nickel maraging steel	(1) 30'dia x 25' deep tank	20 ton mobile	explosive
Tungsten	(2) 20'dia x 12' deep tank	10 ton mobile	
6Al-4V Titanium			
301 Stainless steel			
2219 Al			
Other aluminum alloys			
Other stainless steel alloys			
High strength steels			

Considerable activity in explosive welding/bonding and powder compaction.

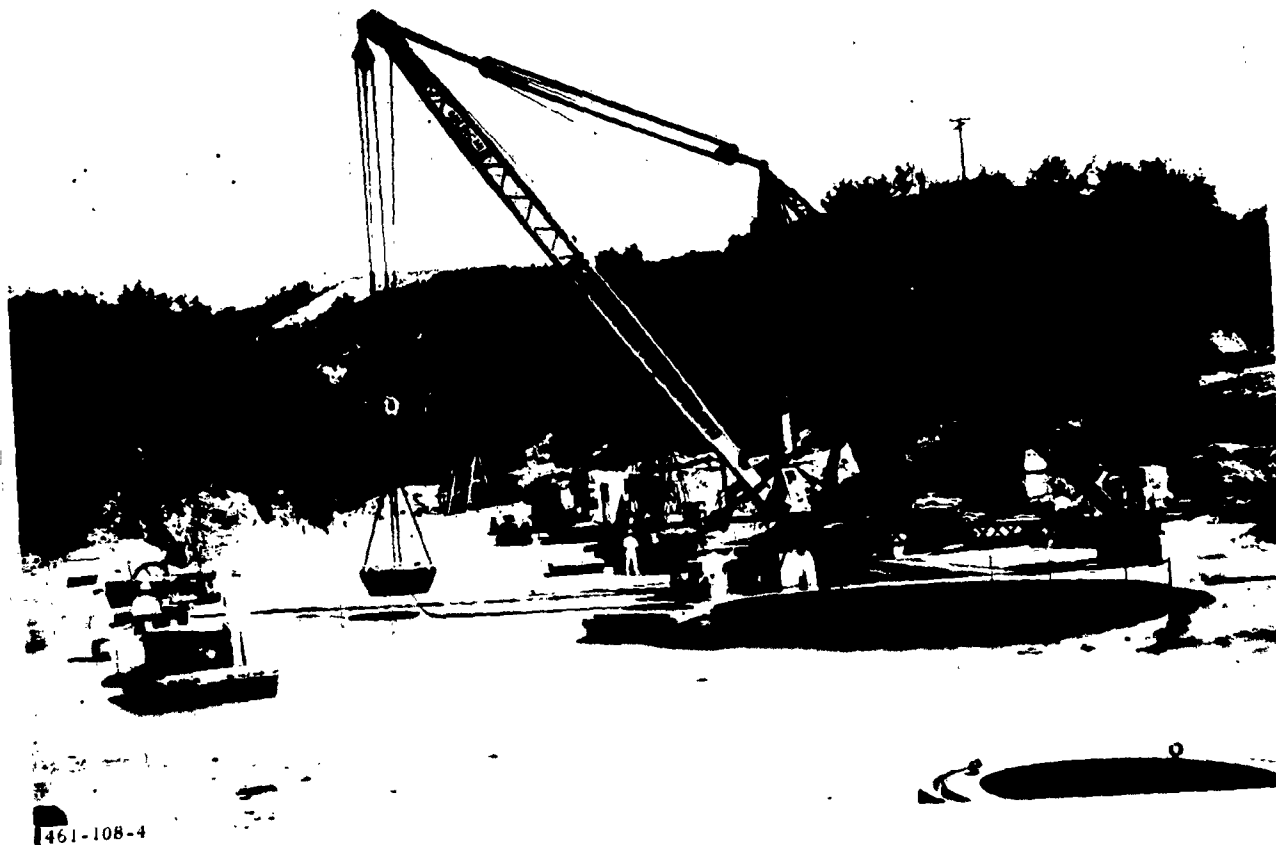


Figure 16. Reprinted by special permission from Aerojet-General Corporation from Report No. 1313-64(01)ER, February 1964. "NOTICE: Certain of the processes and apparatus described herein are patented by Aerojet-General Corporation or are the subject of pending applications. Before reproducing or using apparatus, or practicing processes described, inquiry should be made of Aerojet-General Corporation as to whether the particular invention or inventions are subject to royalty-free use by the Government."



Figure 17. Reprinted by special permission from Aerojet-General Corporation from Report No. 1313-64(01)ER, February 1964. "NOTICE: Certain of the processes and apparatus described herein are patented by Aerojet-General Corporation or are the subject of pending applications. Before reproducing or using apparatus, or practicing processes described, inquiry should be made of Aerojet-General Corporation as to whether the particular invention or inventions are subject to royalty-free use by the Government."

THE BOEING COMPANY
Renton, Washington
(Started 1958)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
1020 Steel	4' wide x 12' long	20 ton mobile	5#
4330M steel	8' dia domes		
321 stainless steel	20' dia x 9' deep tank		
301 stainless steel			
17-7 stainless stl			
347 stainless steel			
2024 alum alloy			
6061 alum alloy			
7075 alum alloy			
2219 alum alloy			
3003 alum alloy			
J 1500			
Hastalloy X			
Rene' 41			
Inconel X			
Mo-.5Ti			
Multimet			
6AL-4V Ti			
8-1-1 Ti			

THE BOEING COMPANY
Wichita, Kansas
(Started)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
Aluminum alloys	(1) 48" dia x 72"	5 ton overhaul	120 grams
Stainless steels	deep underground		PETN (Under- ground)

CHRYSLER MISSILE DIVISION
Detroit, Michigan
(Started prior to 1959)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
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DOUGLAS AIRCRAFT DIVISION
Long Beach, California
(Started)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
Stainless steel 4340 (sized) 6061 Al (sized) Titanium (sized) 1020 Steel (sized)	(1) 108" dia x 120" deep tank 84" dia hemi- sphere sizing possible 60" dia hemi- sphere forming possible	22.5 ton trav- eling	500 grams



Figure 18. Courtesy of Douglas Aircraft Company, Inc.

DOUGLAS AIRCRAFT CORPORATION
 Santa Monica, California
 (Started 1959)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
2014 Alum annealed 2014 Alum W con- dition	(1) 18' dia x 11' deep tank Maximum possible part is 14' dia 1/4" thick 2014 T ⁴ Alum	250# Stationary 15 ton mobile	1400 grams of RDX

EXPLOSIFORM, INC.
 Park Forest, Illinois
 (Started 1961)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
Aluminum Extra low carbon steel AISI 4130 steel D6AC steel Rene' 41 18% nickel maraging	Open air direct con- tact technique 2 to 3 ft. dia. (approx) formed: max. size limited by explosive charge	None on site	30#

GENERAL DYNAMICS/ASTRONAUTICS
 San Diego, California
 (Started 1961 (50))

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
-----	(1) 12' dia x 10' deep tank 1/2" thick x 5' dia parts have been formed	5 ton	-----

This organization has done a considerable amount of work with low explosive forming.

GENERAL DYNAMICS/FORT WORTH
Fort Worth, Texas
(Started 1955)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
Hastalloy X	6-8' dia hemi-	-----	6 sticks dy-
Aluminum (all com-	sphere possible		namite with
mercial sheet	18' dia gentle curve		65% gelatin
grades)	possible: presently		
Titanium	constructing new		
Beryllium (hot)	facility		
1010 Steel			
Alloy steels			
Columbium			
300 series Stain-			
less			
L-605			
Some plastics			

Some open-air forming experimentation. Considerable work with explosive welding/bonding.

GRUMMAN AIRCRAFT ENGINEERING CORPORATION
Bethpage, Long Island, New York
(Started prior to 1959)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
2024 - O (Sheet)	(1) 11' dia x 6'	20 tons at	450 grams at
2024 - W (Sheet)	deep tank at	Bethpage;	Bethpage:
2024 - T3 (Sheet)	Bethpage	30 tons planned	New facility
6061 - O (Sheet)		for Peconic	to be built
7075 - O (Tubing)		River facil-	at Peconic
4130 (Tubing)		ity	River to
4140 (Tubing)			have 14#
304 (Tubing)			underwater
321 (Tubing)			and 5# in air
347 (Tubing)			
Beginning work on			
open air forming			



Figure 19. Courtesy of Grumman Aircraft Engineering Corporation

LING-TEMCO-VOUGHT
Grand Prairie, Texas
(Started 1959)

<u>Materials</u> <u>Successfully</u> <u>Formed</u>	<u>Maximum Part Size</u> <u>Formed and/or</u> <u>Facility Size</u>	<u>Crane</u> <u>Capacity</u>	<u>Maximum</u> <u>Explosive</u> <u>Charge</u>
5086-H32 Al 321 Stainless steel: tested following, but not necessarily successfully formed; 2024-T3 Al A-286 AM-350 L-605 Rene' 41 PH 15-7 Mo Ti-8Al-1Mo-1Va Ti-13Va-11Cr-3Al T2M Cb-752 Vascojet 1000	70" dia x 15" deep dome formed: (1) 22' dia x 12" deep tank	15 ton	Underwater: 900 grams RDX 900 grams PETN 1530 grams TNT Open Air: 1170 grams TNT 690 grams PETN 690 grams RDX

LOCKHEED - CALIFORNIA COMPANY
Burbank, California
(Started 1956)

<u>Materials</u> <u>Successfully</u> <u>Formed</u>	<u>Maximum Part Size</u> <u>Formed and/or</u> <u>Facility Size</u>	<u>Crane</u> <u>Capacity</u>	<u>Maximum</u> <u>Explosive</u> <u>Charge</u>
Aluminum: 2014 2024, 6061, 2019, 7075 Other alum alloys Stainless Steels: 302, 321, AM 350, 17-7 1H Other stainless steel alloys Commercially pure Ti 8 Mn Ti 6Al-4Va Ti 120 VCA Ti Other Ti alloys HM 21 A-T8 HK 31AH24 Other magnesium alloys	15' dia largest pos- sible (1) tank 14' dia x 15' deep aboveground	10 ton	5-6# PETN Open air; 420 grams Underwater

LOCKHEED-CALIFORNIA COMPANY (Cont'd)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
Steel: 1010, 1018 1020, 4130, 4340 Vascojet 1000 Copper Silicon Bronze Rene' 41 Other alloys			



Figure 20.
Courtesy of
Lockheed-
California
Company

LOCKHEED-GEORGIA COMPANY
Marietta, Georgia
(Started 1956)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
Aluminum Titanium Stainless Steels: 420, 301 Inconel-X Nickel alloys	(1) 100' long x 40' wide x 20' deep pond	20 ton mobile	2 1/2 - 60% nitroglyc- erin dynamite underwater; 6-8# - 60% nitro- glycerin dyna- mite open air

Have done some open air work.

Figure 21.
Courtesy of
Lockheed Air-
craft Corpor-
ation.



MARTIN COMPANY
Denver, Colorado
(Started 1958)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
2014-0 Alum	10' dia domes formed	2 ton: can get	20# high ex-
2219-0 Alum	(1) tank 105' dia	50 ton crane	plosive on
2219-T37 Alum	(approx) x 22' deep	from plant	large tank
2219-T31 Alum	(1) 7' dia tank		
18% nickel maraging steel	(1) 3' dia tank		
Ti-6Al-4V	Plans for building		
Ti-5Al-2.5 Sn	25' dia x 10' deep		
1020 Steel	tank		
7039 Alum			
Tantalum alloys			
Gold foil			
Columbium alloys			
Copper alloys			
300 series stain- less steels			
Honeycomb (metal and phenolic)			
5083 Alum			
6061 Alum			
1100 Alum			

Have performed some open-air forming and some shock hardening.

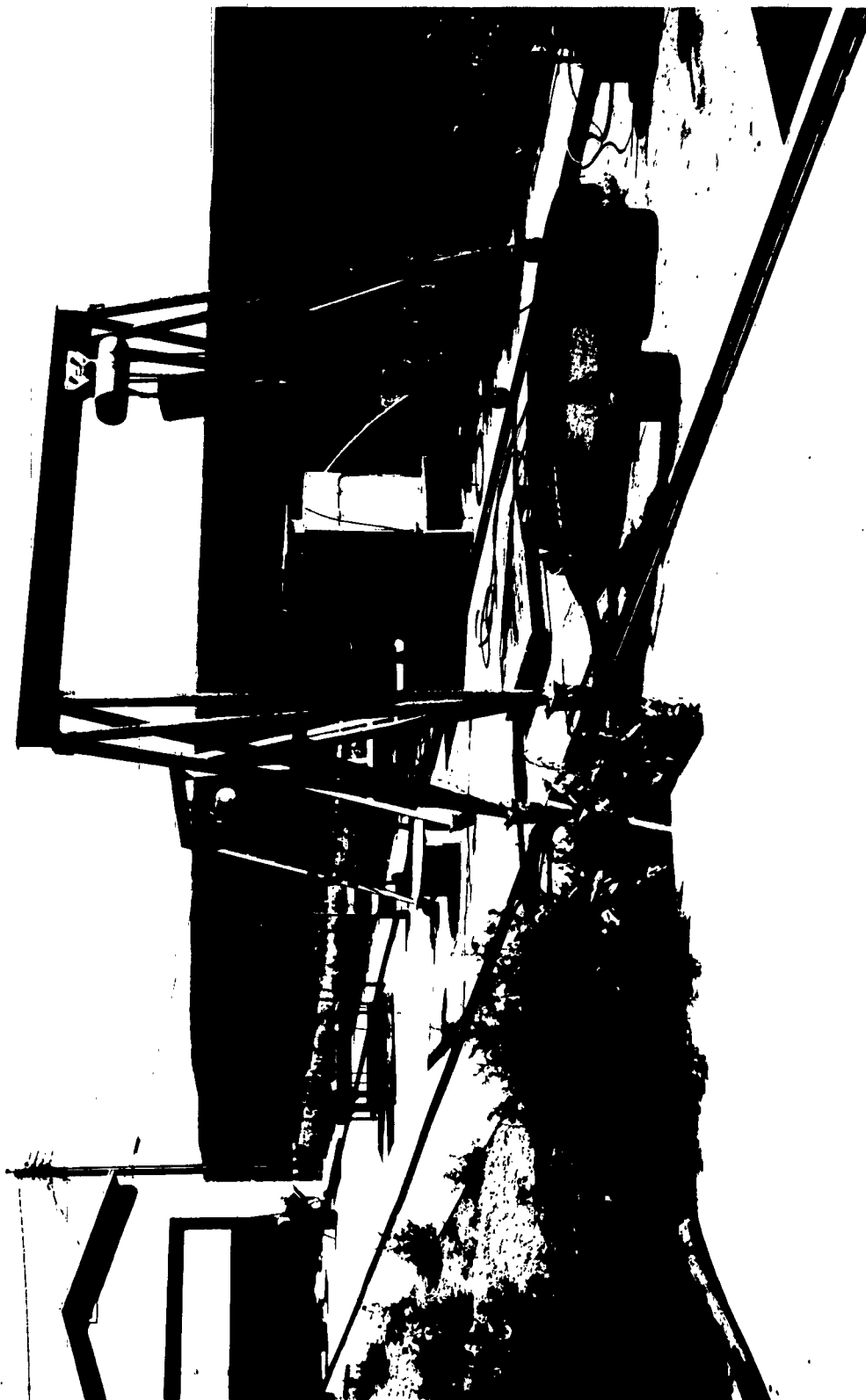


Figure 22. Courtesy of Martin Company



Figure 23. Courtesy of Martin Company

METRO ENGINEERING CO., INC.
 East Hampton, Massachusetts
 (Started)

<u>Materials</u> <u>Successfully</u> <u>Formed</u>	<u>Maximum Part Size</u> <u>Formed and/or</u> <u>Facility Size</u>	<u>Crane</u> <u>Capacity</u>	<u>Maximum</u> <u>Explosive</u> <u>Charge</u>
--	--	---------------------------------	---

This firm performs limited work when they can manufacture the tooling for the forming operation. They only do this type of work when one of their regular customers confronts a problem in forming a part.

THE MOORE COMPANY
 Marceline, Missouri
 (Started 1950)

<u>Materials</u> <u>Successfully</u> <u>Formed</u>	<u>Maximum Part Size</u> <u>Formed and/or</u> <u>Facility Size</u>	<u>Crane</u> <u>Capacity</u>	<u>Maximum</u> <u>Explosive</u> <u>Charge</u>
Monel	Parts formed to 36" dia (fan hubs)	-----	-----

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
 Huntsville, Alabama
 (Started)

<u>Materials</u> <u>Successfully</u> <u>Formed</u>	<u>Maximum Part Size</u> <u>Formed and/or</u> <u>Facility Size</u>	<u>Crane</u> <u>Capacity</u>	<u>Maximum</u> <u>Explosive</u> <u>Charge</u>
7039 Alum	(1) 25' dia x 15'	12.5 tons	8# high ex-
2219 Alum	deep tank		plosive un-
316 CRES	(1) 15' dia x 12'		derwater:
2014-T451 Alum	deep tank		1/2# high ex-
321 Stainless	(1) 7' dia x 6' deep		plosive open
steel	tank		air

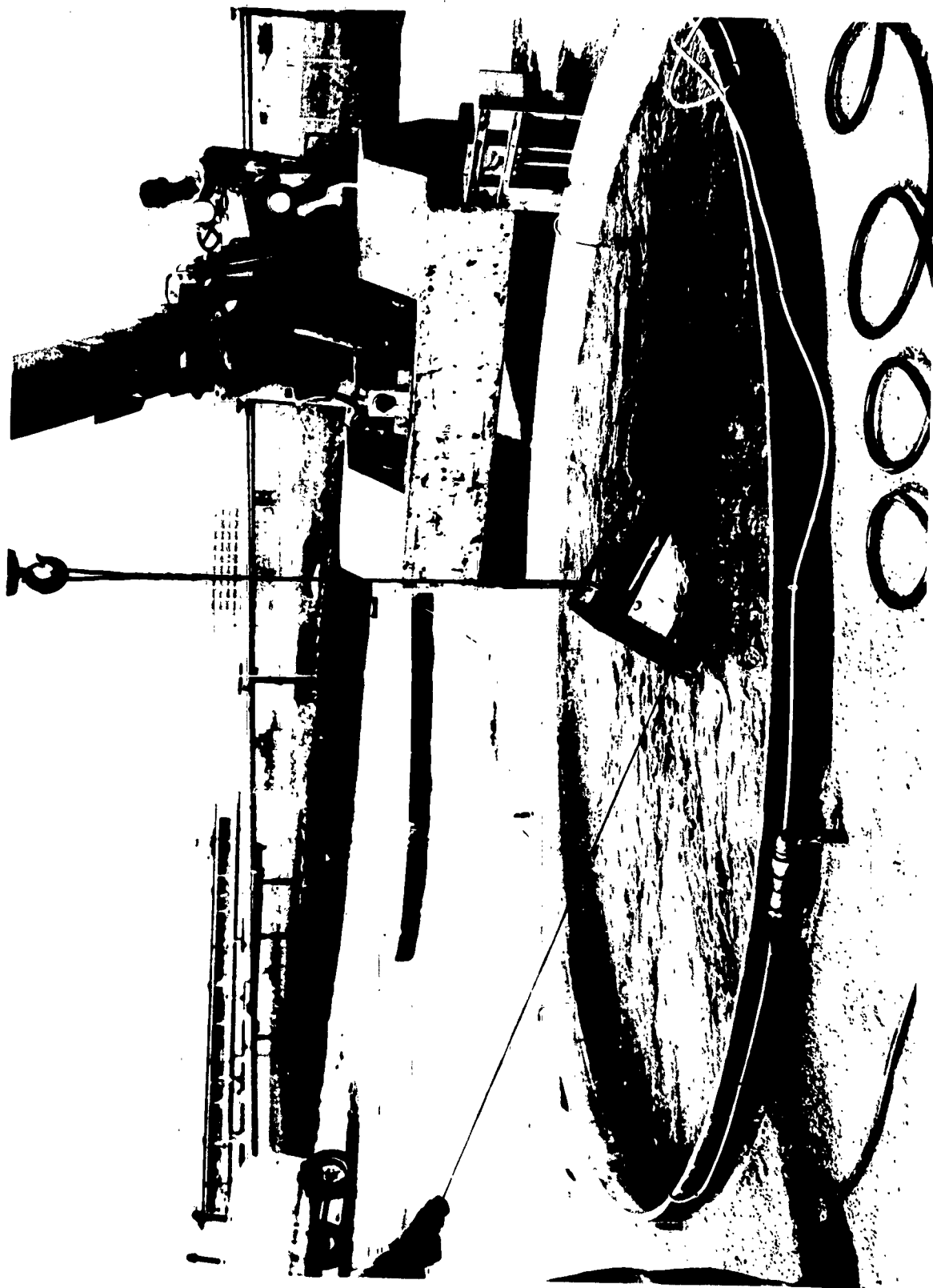


Figure 24. Courtesy of NASA Marshall Space Flight Center

FLARE-NORTHERN DIVISION
(formerly National Northern)
ATLANTIC RESEARCH CORPORATION
West Hanover, Massachusetts
(Started 1957)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
Carbon steels Alloy steels Stainless steels Nickel alloys Alum alloys Magnesium alloys Titanium alloys Copper alloys Tantalum Uranium Zircaloy-2 Beryllium Columbium Tungsten Molybdenum	Facility capable of approximately 4 to 6" thick part to 10' diameter	-----	50 to 100#

This organization has experimented with explosive welding, forging and powder compaction.

NORTH AMERICAN AVIATION, INC.
Columbus, Ohio
(Started prior to 1961)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
6061-0 Alum 7075-0 Alum 304 Stainless 321 Stainless P15-7Mo Stainless AM 350 Stainless 1010 Carbon steel 6Al-4V Ti	9' dia part formed (53) (1) 15' deep tank with 10' dia at bottom and 18' dia at top	-----	2# TNT



H-96-200C II-22-60

Figure 25. Courtesy of North American Aviation, Inc.

NORTH AMERICAN AVIATION, INC.
El Toro, California
(Started 1958)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
SO Alum	25' die maximum part	(1) 40 ton mobile	12# PETN
2014-T4 Alum	size without facil-		so far
321 Stainless	ity modification		
Rene' 41	(2) 25' dia x 15' deep	(1) 80 ton gantry	
1020 carbon steel	(2) 25' dia x 15' deep	(1) 10 ton gantry	
4130 Steel			
6061 Alum			
2024 Alum			
PH15-7 Mo			
Inconel			
Magnesium			
Titanium			
Tantalum			
2 Alloy steels			
2219 Alum			
OS-10613A Class II			
alloy steel			
304 Stainless			
Molybdenum			
Copper			
Tungsten			
Hastalloy C			
Teflon			
Kel-F			

This firm has worked with explosive cladding and powder compaction.



Figure 26. Courtesy of North American Aviation, Inc.

PRATT & WHITNEY AIRCRAFT
East Hartford, Connecticut
(Started 1961)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
Titanium	(1) 8' dia tank	20 ton	17,000 grains
Udimet	(1) 5' dia tank		of sheet ex-
Aluminum			plosive so far
Hastalloy X			
Inconel			
Waspalloy			
Nickel steel			
Columbium			
Stainless steel			

This corporation has used explosives to weld, clad, and shock harden materials.



Figure 27. Reprinted by special permission from PRATT & WHITNEY AIRCRAFT DIVISION, UNITED AIRCRAFT CORPORATION.

RYAN AERONAUTICAL COMPANY
San Diego, California
(Started 1956)

<u>Materials Successfully Formed</u>	<u>Maximum Part Size Formed and/or Facility Size</u>	<u>Crane Capacity</u>	<u>Maximum Explosive Charge</u>
HP9-4-25 Aluminum alloys Maraging steels 4340 Steel D6AC H-11 17-7 PH Stainless AM 350 Stainless Titanium alloys Molybdenum Tungsten 8286 Haines 25 Inconel Inconel X Hastalloy X K monel 321 Stainless Rene' 41 A-286	(1) 10' dia x 8.5' deep tank	5 ton	100 grams

Other firms which have been cited as being active in explosive forming are (53):

Martin Company	Baltimore, Maryland
Nitroform	Detroit, Michigan
Standard Steel Works	Burnham, Pennsylvania
Budd Company	Philadelphia, Pennsylvania
Taylor-Wharton	Easton, Pennsylvania
Manganese Steel Forge	Philadelphia, Pennsylvania
American Manganese Steel	Chicago Heights, Illinois
Battelle Memorial Institute	Columbus, Ohio
Stanford Research Institute	Menlo Park, California
A. D. Little	Cambridge, Massachusetts

An indication of the interest expressed by other countries is indicated by the following partial listing:

CARDE (presently inactive (19))	Canada
Canada Industries, Ltd.	Canada
Bristol Air Industries, Ltd. (7)	Winnepeg, Canada
Orenda Engines, Ltd. (7)	Canada

Sorrel Industries
 Production Engineering Research
 Associates (54)
 Vickers-Armstrong, Ltd.
 Central Institute for Industrial Research(56)
 (Joint U.S.-Norway Venture)
 Scientific Research Institute of Aircraft
 Technology (57)

Canada

Great Britain

Great Britain

Norway

USSR

Bulgaria (56)

France (53)

Holland (53)

Ireland, North (53)

Japan (53)

Switzerland (53)

West Germany (53)

i. Discussion of Applications and Pictorial Illustrations: It is the intent of this section to familiarize U. S. Army Materiel Command personnel with the types of material and configurations which have been historically formed and/or sized through the use of explosives.

A comparative rating of the entire set of explosive forming techniques was made by Ling-Temco-Vought in July, 1963. The results of their analysis are presented in Table 13 below:

TYPICAL SYSTEM CHARACTERISTICS		EXPLOSIVE FORMING SYSTEMS			
		HIGH EXPLOSIVE	LOW EXPLOSIVE	EXPLOSIVE GAS	
TYPE OF SYSTEM	OPEN	R.T.	A	E	E
		E.T.	C	E	E
	CLOSED	R.T.	E	A	B
		E.T.	E	A	B
ENERGY TRANSFER MEDIA	R.T.		WATER RUBBER	AIR WATER RUBBER	GAS
	I.T.		OIL RUBBER GLASS SALT	AIR	GAS
	H.T.		MOLTEN METAL SAND	AIR	GAS
RELATIVE CYCLE TIME		HIGH		MEDIUM	MEDIUM
LOCATION REQUIREMENTS		REMOTE		SEPARATE	SEPARATE

SYMBOLS: R.T. - ROOM TEMPERATURE
 E.T. - ELEVATED TEMPERATURE
 I.T. - INTERMEDIATE TEMPERATURE
 H.T. - HIGH TEMPERATURE

RATINGS: A - EXCELLENT
 B - GOOD
 C - FAIR
 D - POOR
 E - INAPPLICABLE

Table 13. Reprinted by special permission from Research and Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, from Report No. ASD-TDR-63-7-871, dated July 1963.

Steel Magazine cited a Battelle Memorial Institute analysis of high energy rate methods which is presented in Table 14 below:

REFORMING

Battelle Defines State-of-the-Art

	HIGH EXPLOSIVES	PROPELLENTS	GAS MIXTURES	HIGH PRESSURE GAS	EXPLODING WIRE	ELECTRIC DISCHARGE	MAGNETIC FIELD
	have size capability	can be employed in hand tools	can form thin parts to close tolerances	works best in forging & extrusion	makes exact replicas repeatedly	offers simplicity	handles tube or cylinder reduction
STATE-OF-THE-ART	Blanking, coining, powder compaction, drawing, extruding, drawing, expanding, flanging, hardening, joining, sitting, stretching, and inspection	Bulging, compacting, sizing, and driving, machining	Bulging, sizing and stretching	Compacting, drawing, extruding, forging, stretching, spinning	Bulging, stretching, piercing	Bulging, stretching, piercing	Swaging, joining, shrinking
REMARKS	None	Limited by size of a closed pressure (5 ft diameter max)	container which will hold the pressure	Present, 10 in diameter future, 35 in diameter	Present, 5 ft diameter future, 10 ft diameter	Present, 5 ft diameter future, 10 ft diameter	Present, 1 ft diameter future, 4 ft diameter
REMARKS	Good	Poor	Fair	Excellent	Good	Fair	Fair
REMARKS	Poor	Poor	Fair	Excellent	Good	Good	Fair
REMARKS	4,000 to 25,000 fps	1,000 to 8,000 fps	1,000 to 8,000 fps	50 to 200 fps	20,000 fps	20,000 fps	10,000 to 20,000 fps
REMARKS	High	Medium	High	Low	High	Medium	Medium
REMARKS	Medium	Medium	Medium	Very low	Medium	Low	Medium
REMARKS	High	Medium	High	Low	Medium	Medium	Low
REMARKS	High	High	Low	Medium	Low	Low	Low
REMARKS	Low	Medium	High	Medium	Medium to high	Medium to high	High
REMARKS	None	None	4 months	2 to 6 months	6 months	6 months	8 months
REMARKS	Only personnel trained and competent in the application of explosives and propellants should operate	Only technicians with complete knowledge of exploding gas mixtures	Conventional guards, and interlocking switches, as with presses	Restricted access and safety interlock required as with all high tension equipment	Separate	Separate	Separate
REMARKS	Remote	Separate	Unrestricted	Separate	Separate	Separate	Separate

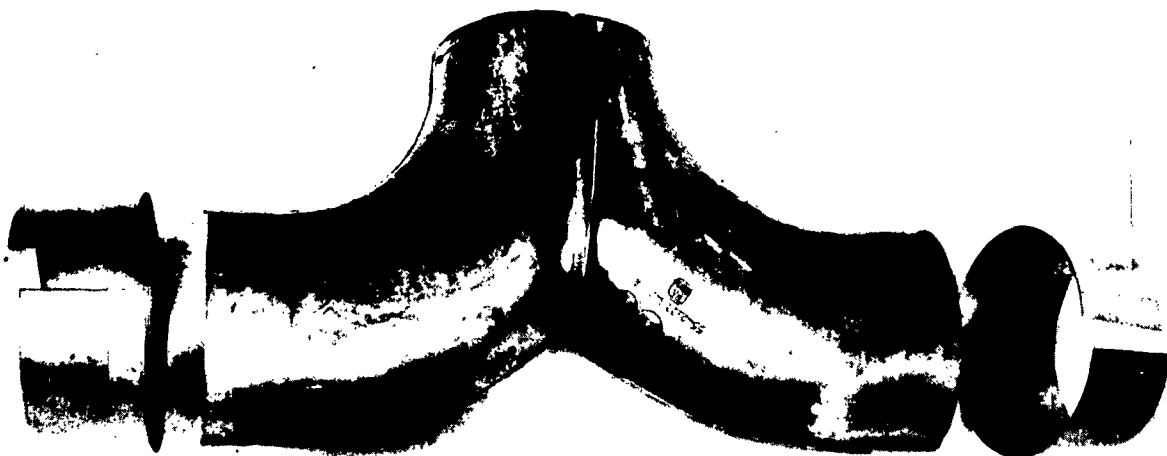
Table 14. Reprinted by special permission from THE PENTON PUBLISHING COMPANY from the article "Machines Turn Violence Into Forming Profits" as published in the 6 August 1962 issue of STEEL. C 1962

(1) Low Explosive - Closed Die: This technique has experienced decreased usage because of the establishment of shops which are capable of producing small quantities of parts through the use of the electrohydraulic and magnetic forming methods. However, some producers still prefer this technique for relatively small lots of small parts. This is particularly true for tube bulging operations.

Figure 28 below is an example of the manner in which the low explosive technique can simplify the construction of tubing. The new method eliminated 89 operations.



A. NEW DUCT ASSEMBLY



B. OLD DUCT ASSEMBLY

Figure 28. Courtesy of General Dynamics/Astronautics.

Figure 29 below illustrates the setup used to form the center tee on the steer horn assembly shown above:

THIS PHOTO SHOWS A SHOTGUN FORMED 90° REDUCER

ELBOW. A 2.50 DIA X .028 321 CRES TUBE IS

PRE-FORMED TO 86° TO FIT DIE CAVITY. THE

FINISH PART IS 3.0 DIA WITH 2.50 REDUCER AT

LOWER END

NOTE: THE AMOUNT OF DRAW

NO INTERSTAGE ANNEAL

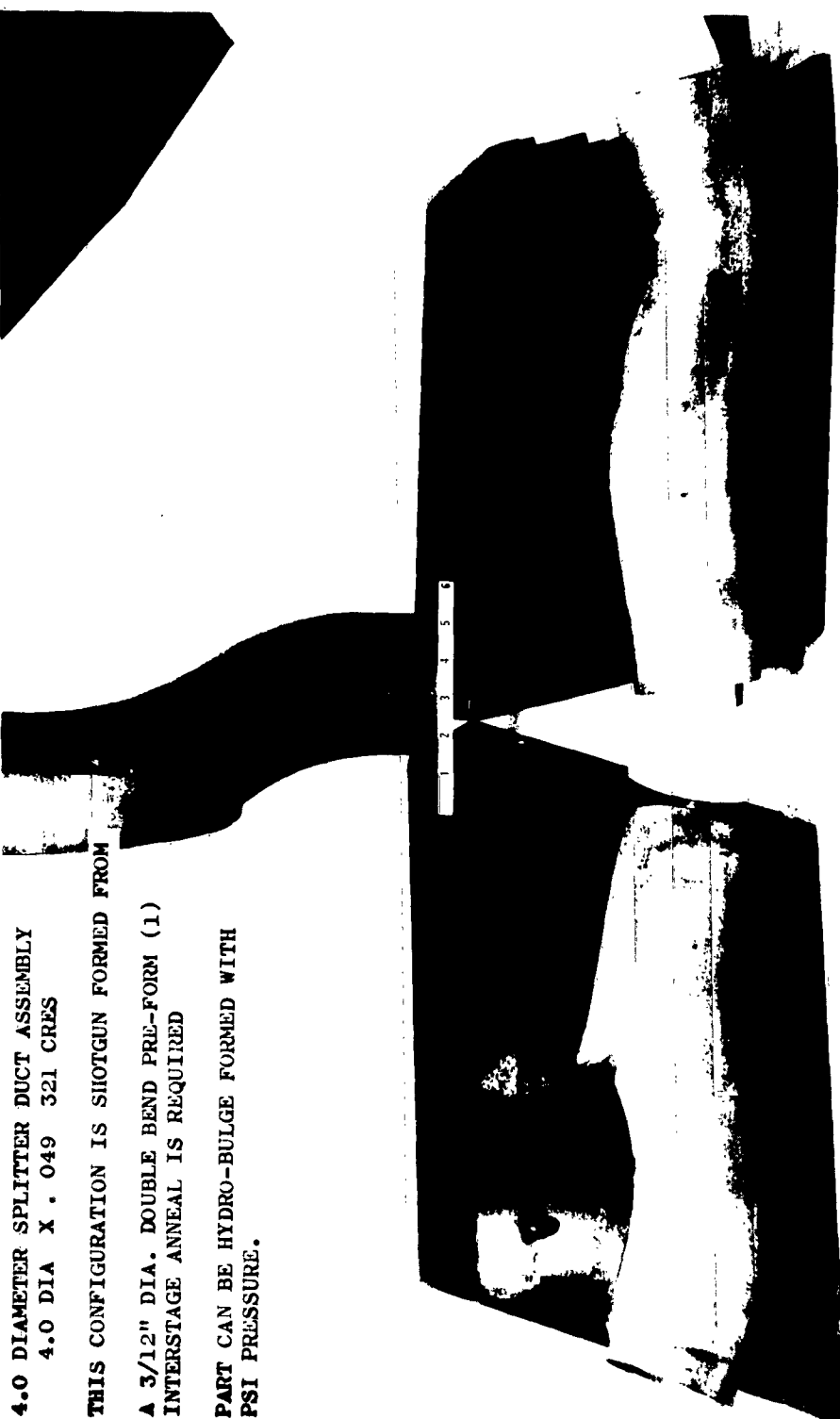
"Courtesy of Astronautics Division,

General Dynamics Corp."



Figure 29. Courtesy of General Dynamics/Astronautics

Figures 30 through 34 depict applications of low explosive forming developed by General Dynamics Astronautics. The setups shown in Figures 32 and 33 were used to form 321 CRES material. The part shown in Figure 34 was made of K-monel.



4.0 DIAMETER SPLITTER DUCT ASSEMBLY
4.0 DIA X .049 321 CRES

THIS CONFIGURATION IS SHOTGUN FORMED FROM

A 3/12" DIA. DOUBLE BEND PRE-FORM (1)
INTERSTAGE ANNEAL IS REQUIRED

PART CAN BE HYDRO-BULGE FORMED WITH
PSI PRESSURE.

Figure 30. Courtesy of General Dynamics/Astronautics

4.0 DIA X 5.0 DIA. ELBOW LINE REDUCER.
3.5 DIA. .028 WALL CRES TUBE FORM BLANK
SHOTGUN FORMED TO FINISH CONFIGURATION
1 INTERSTAGE ANNEAL

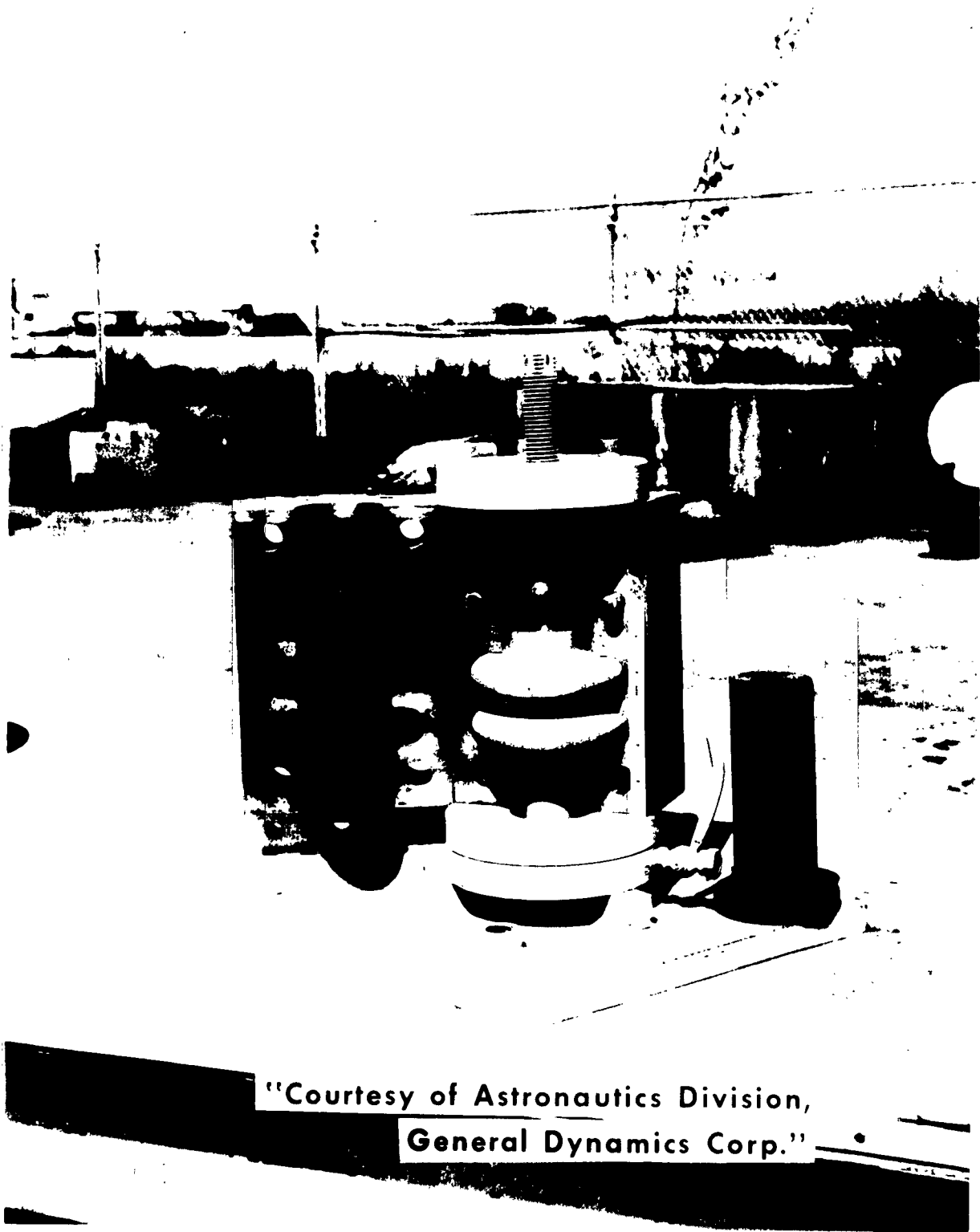
NOTE: PART CAN BE BULGE FORMED WITH OIL
OR WATER PRESSURE IF NO EXPLOSIVE
CAPABILITY IS AVAILABLE.



Figure 31. Courtesy of General Dynamics/Astronautics



Figure 32. Courtesy of General Dynamics/Astronautics



"Courtesy of Astronautics Division,
General Dynamics Corp."

Figure 33. Courtesy of General Dynamics/Astronautics

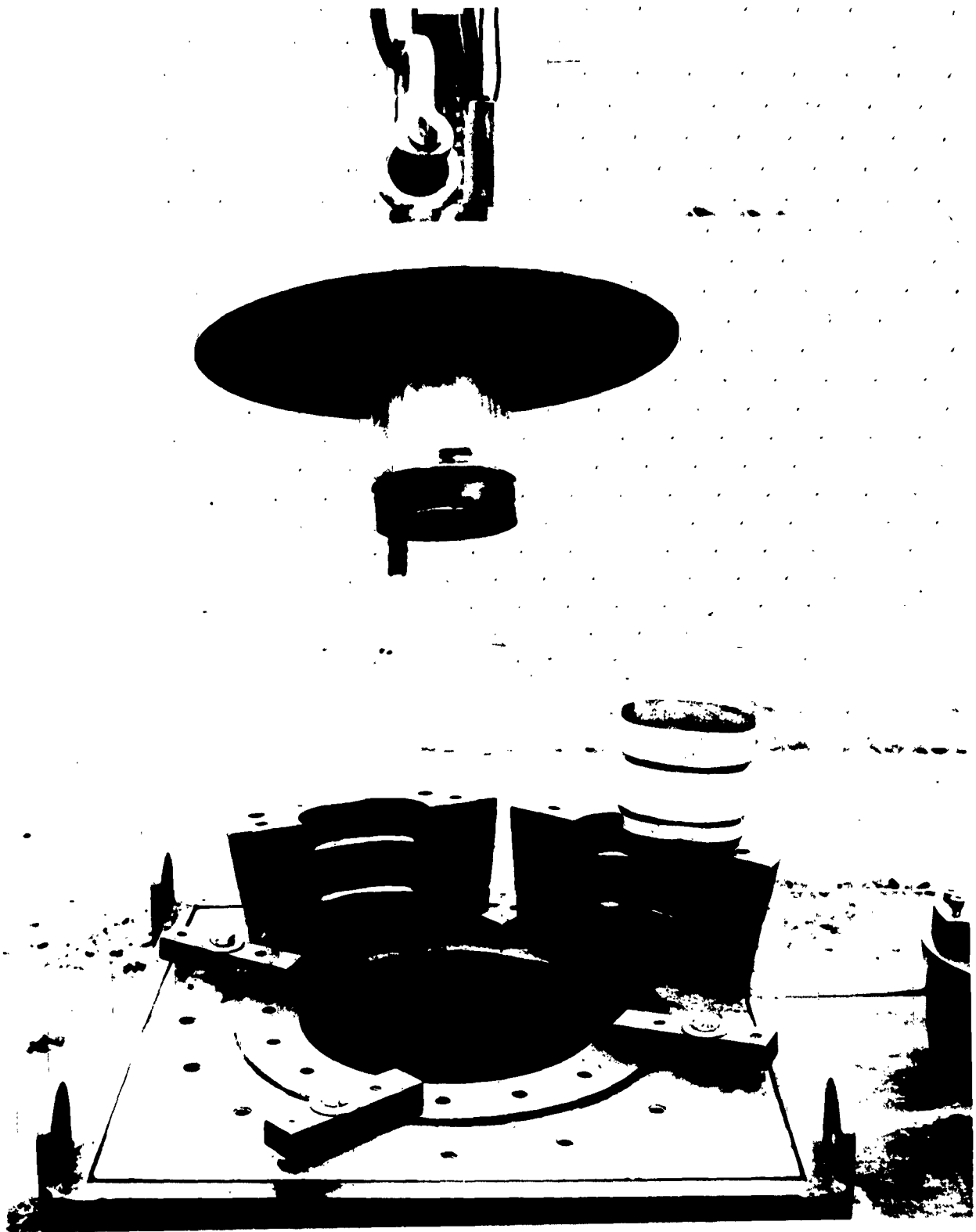


Figure 34. Courtesy of General Dynamics/Astronautics

Figures 35, 36, and 37 illustrate further applications developed by the Winchester-Western Division of Olin Mathieson Chemical Corporation.

PROBLEM: To double bulge form a cylindrical tube of Type 304 or Type 310 stainless steel tubing $\frac{3}{8}$ " O.D. having a wall thickness of .035" and being $2\frac{1}{4}$ " in length.

Solution: Olin Mathieson Chemical Corporation has solved the above problem whereby two parts are made at the same time. Conventionally, this part required a large number of press operations.

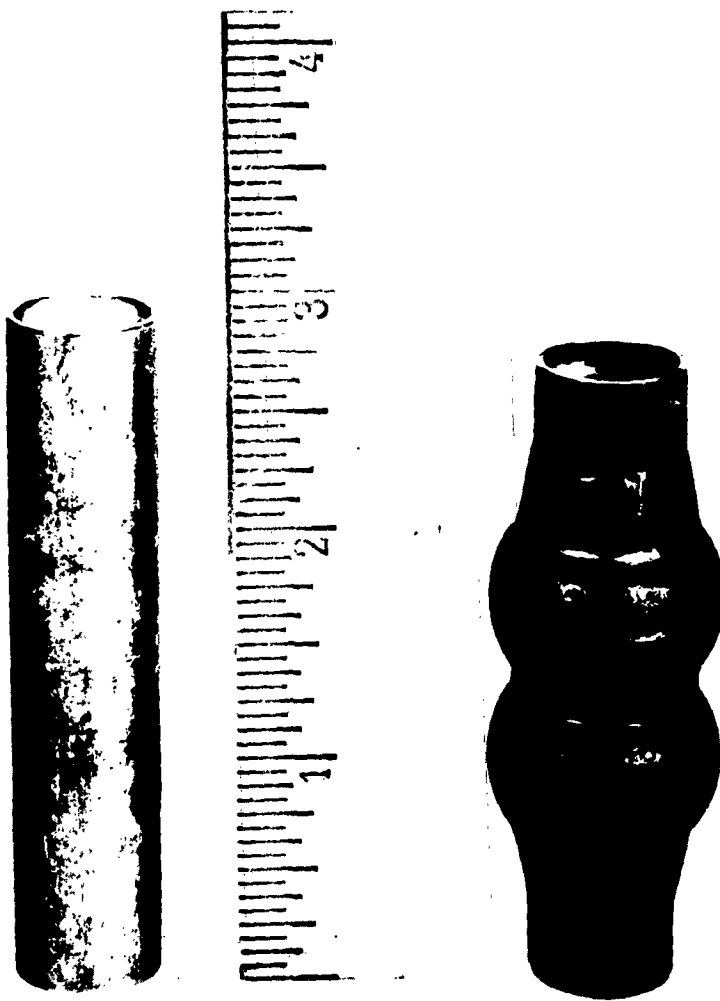


Figure 35. Reprinted by special permission from OLIN MATHIESON CHEMICAL CORPORATION, WINCHESTER-WESTERN DIVISION, from their brochure titled, "SUPER SPEED Metal Forming".



Figure 36. Reprinted by special permission from OLIN MATHIESON CHEMICAL CORPORATION, WINCHESTER-WESTERN DIVISION, from their brochure titled, "SUPER SPEED Metal Forming".

Solution: Olin Mathieson Chemical Corporation has obtained the reduction desired for this particular application. The material was low carbon 1015 steel.

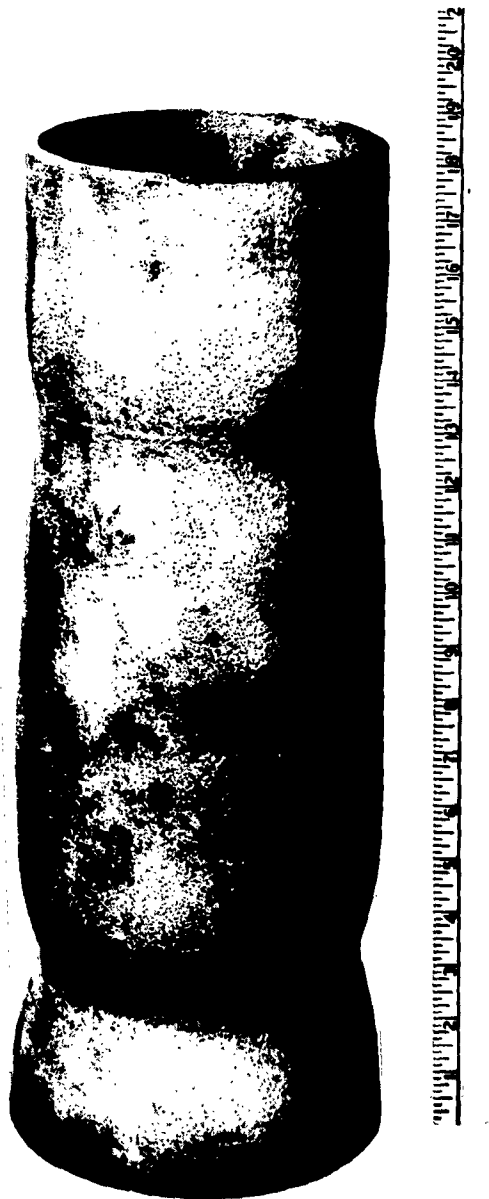


Figure 37. Reprinted by special permission from OLIN MATHIESON CHEMICAL CORPORATION, WINCHESTER-WESTERN DIVISION, from their brochure titled, "SUPER SPEED Metal Forming".

Figures 38, 39, and 40 depict parts formed by Rohr Aircraft Corporation in their low explosive forming program:



Figure 38. - Cartridge formed transition tube made of type 321 stainless welded tubing.



Figure 39. - Interstage connector shroud for T-50 gas turbine engine with rolled and welded preform.



Figure 40. - Explosively formed valve body housing showing feasibility of high local deformation made possible by proper staging operation.

Figures 38, 39, and 49. Reprinted by special permission from a paper by S. P. Jenkins, "High Energy Forming In Production", SP62-82, presented at a Seminar of the AMERICAN SOCIETY OF TOOL AND MANUFACTURING ENGINEERS.
C 1962

Figure 41 illustrates the use of low explosives to shear as well as form a part in one operation.

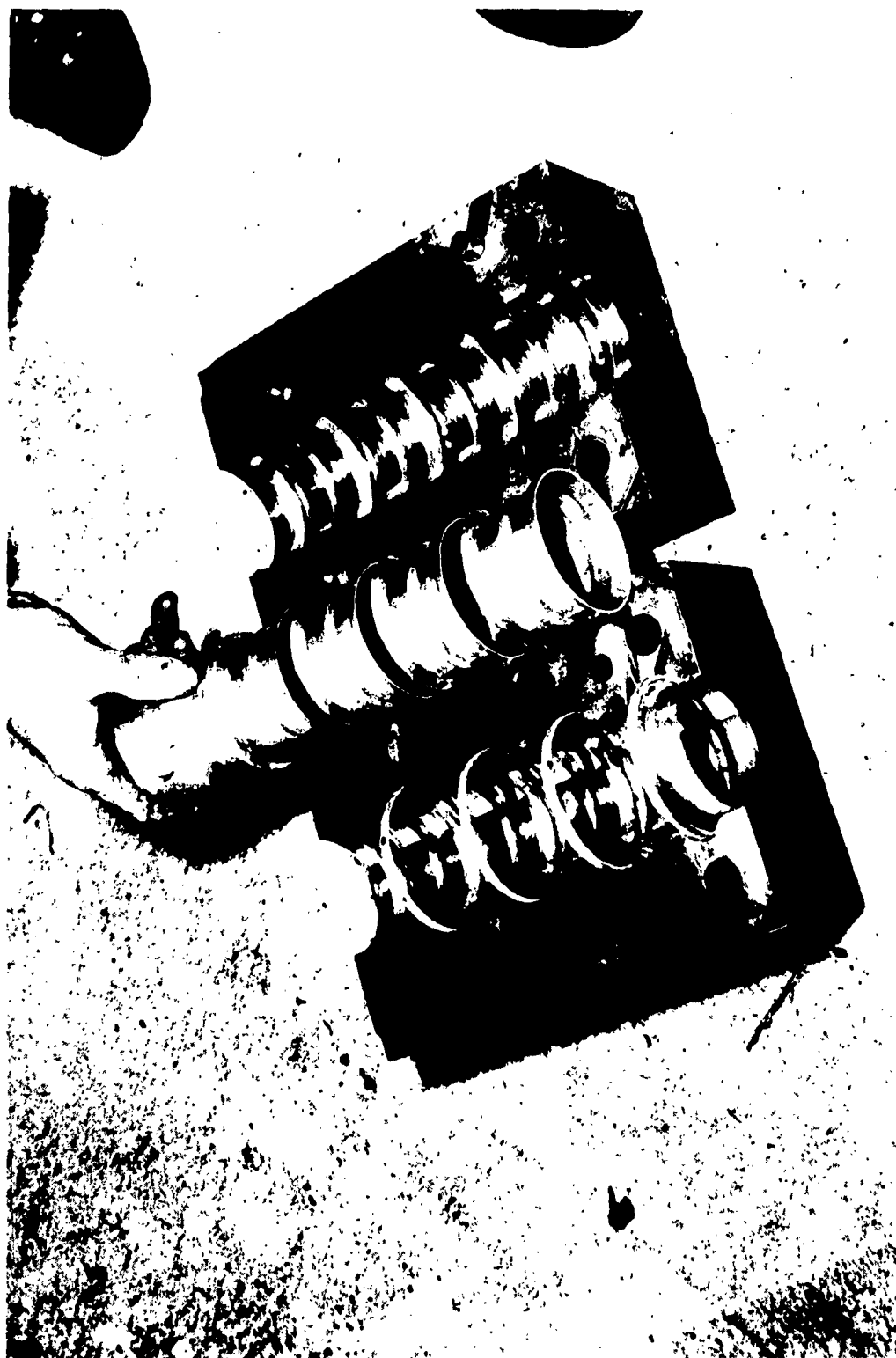


Figure 41. Courtesy of Ling-Temco-Vought

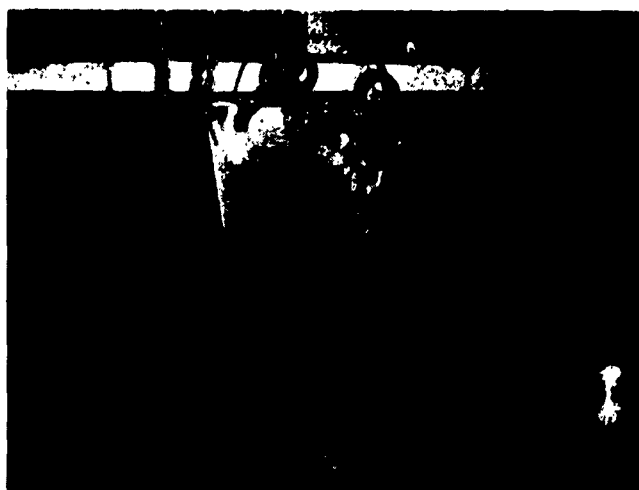
EXPLOSIVE BULGE FORMING DIE WITH FORMED ALUMINUM
PARTS REMOVED. SHEARED ALUMINUM RINGS STILL IN DIE.
UNIT 22320
5 NOVEMBER 1959

Figure 42 illustrates the difficult-to-form configurations which this technique is capable of producing.



MAIN FUEL LINE TUBE AND
FORMING DIE BEFORE FIRST
FORMING OPERATION

FOUR STAINLESS STEEL TUBES
SHOWING THE VARIOUS OPERATIONAL
STEPS



FORMING DIE AND
FINISHED FORMED MAIN
FUEL LINE TUBE

Figure 42. Courtesy of Ling-Temco-Vought

(2) Direct Contact High Explosive: Very little literature exists on this particular forming technique. However, the following three figures illustrate the general setup used by Explosiform, Inc. Figure 43 shows the blank and die prior to charge placement. Figure 44 depicts the charge in place. In this case, the charge is nitroguanadine which is initiated by a blasting cap with a conventional fuse. The finished part is shown in Figure 45. The finished part required radially drilled holes which were distorted by a conventional forming method. This problem was solved by the use of a removable filler material in conjunction with explosive forming.



Figure 43.

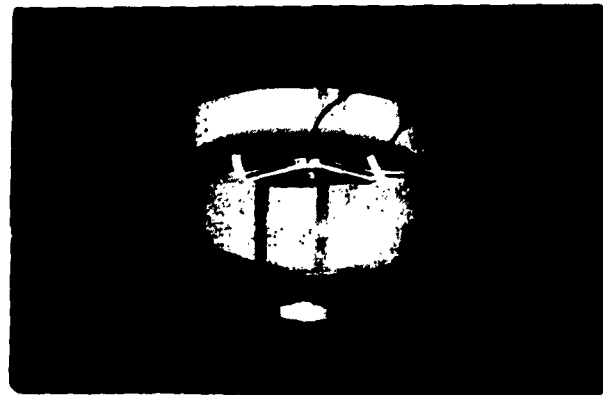


Figure 44.



Figure 45.

Figures 43, 44 and 45,
Courtesy of
Explosiform, Inc.

(3) High Explosive - Open Die: This technique appears to have received the most comprehensive usage as is evidenced by the quantity of literature published on its applications.

(a) Cylindrical and Conical Blank Parts: The Moore Co. has made use of this setup for approximately ten years in the production of fan hubs. Figure 46 below illustrates the technique they have used to form monel hubs.



A cylindrical Monel blank (actually two welded Monel cylinders telescoped within one another) is placed in a heavy laminated steel die. The assembly is partially filled with water and a stick of dynamite suspended at water level. The heavy block shown suspended at right is placed over the die.



The dynamite is set off . . . neatly forcing the Monel into the contours of the die in a single operation.



This is what the Monel hub looks like when removed from the die. The explosive method of forming costs Moore a fraction of the cost of spinning, there is no waste metal, and no time lost for annealing.

Figure 46. Reprinted by special permission from THE INTERNATIONAL NICKEL COMPANY, INC., from PROCESS INDUSTRIES QUARTERLY, September 1954. "MONEL" is a registered trademark of THE INTERNATIONAL NICKEL COMPANY, INC. C 1954

Figure 47 illustrates the feasibility of sizing and piercing a part in one operation. There were no burrs on the holes.

Reprinted by special permission from Aerojet-General Corporation from Report No. 1313-64(01)E1, February 1964. NOTICE: Certain of the processes and apparatus described herein are patented by Aerojet-General Corporation or are the subject of pending applications. Before reproducing or using apparatus, or practicing processes described, inquiry should be made of Aerojet-General Corporation as to whether the particular invention or inventions are subject to royalty-free use by the Government."

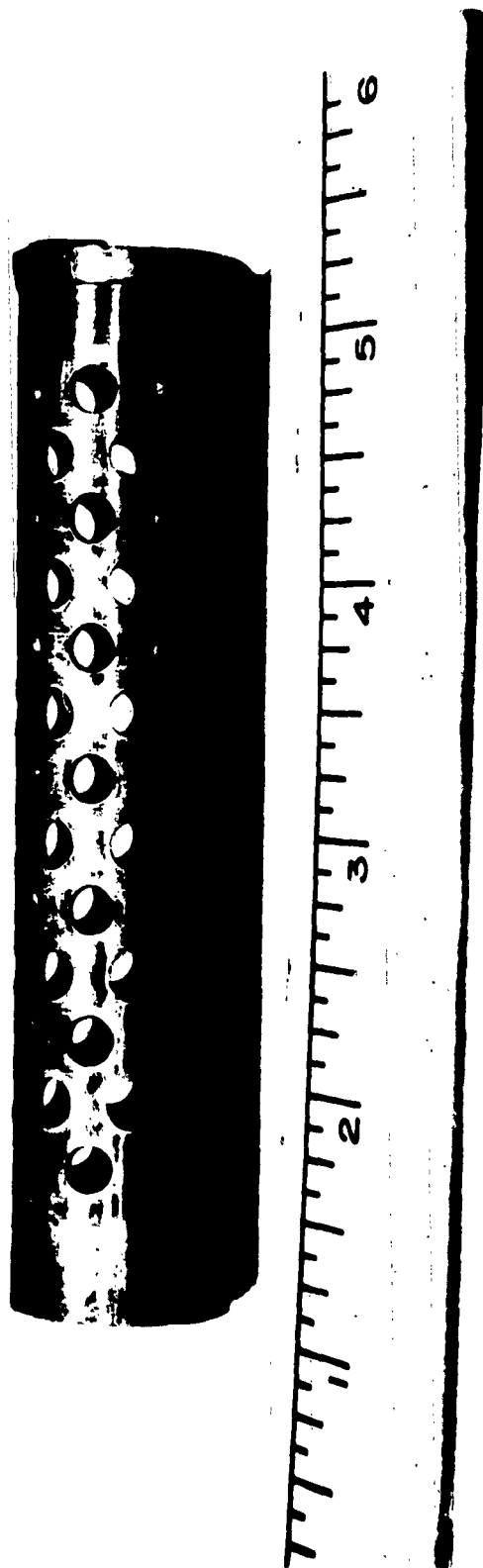


Figure 47. High-Strength Steel Tube Perforated By Use of Explosive Pressures.

Figure 48 illustrates a small aluminum test part which was flanged by North American Aviation. Note the wrinkle-free characteristics of the part.



H-96-158D 6-7-60

Figure 48. Reprinted by special permission from NORTH AMERICAN AVIATION, INC., from Report No. MEP 8006

The 1010 steel part shown in Figure 49 was fabricated from .063" material. Note the smooth surface gained through the use of an epoxy and fiberglass laminate liner on the die surface.



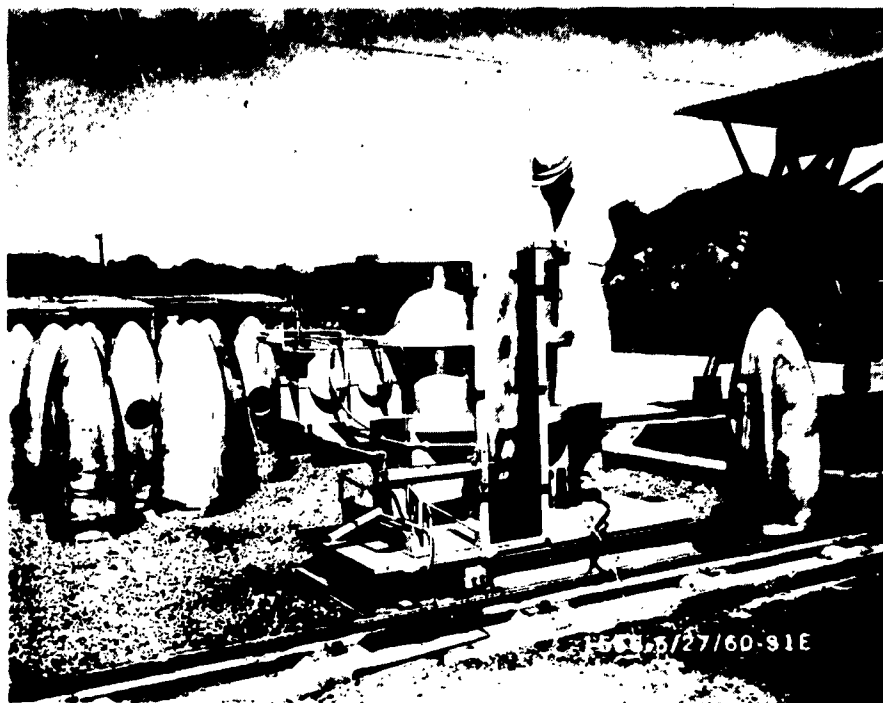
Figure 49. Reprinted by special permission from NORTH AMERICAN AVIATION, INC., from Report No. MEP 8006

The following four figures illustrate the versatility of this forming method.



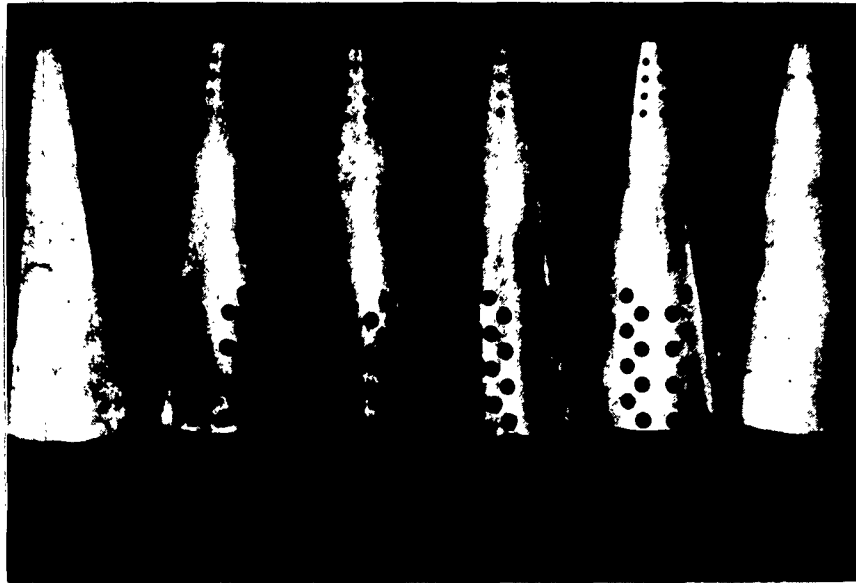
F-1 ROCKET ENGINE PRESSURE BAG

The split die used to form this part is in the background. The part, in the foreground, is made from a straight conical preform of 0.010 inch thick 321 stainless steel.



PYLON FOR THE HOUND DOG MISSILE

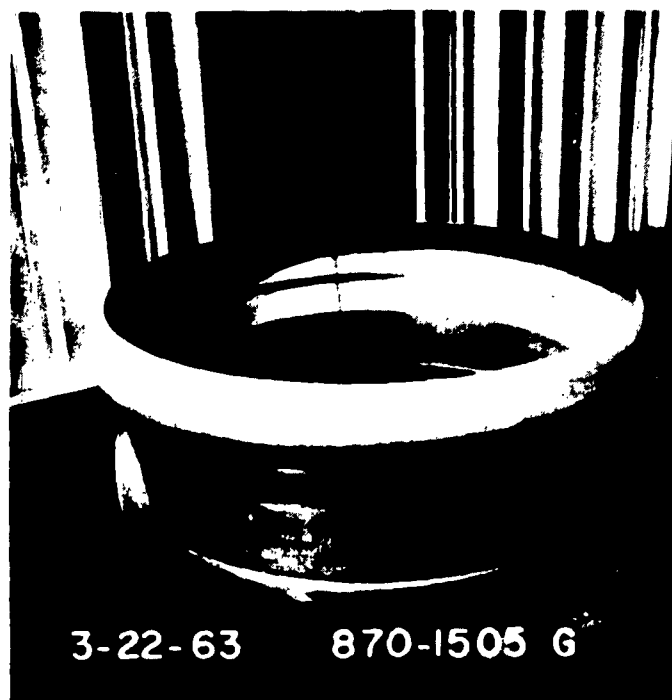
These parts are formed starting with a drop hammered preform, shown at the right. Center of photo shows part explosively bulged in the split die. Completed parts are shown at the left. High Energy Forming of these parts was found to cost one-tenth of the cost of fiberglass pylons and one-fifth of the cost of bulge forming. 600 of these parts were produced.



CONICAL MISSILE PART

This part was explosively sized and all of the holes punched in a single forming operation. The material is 6061-T6 aluminum, one-quarter inch thick. A total of 24 three-quarter inch diameter holes and 32 one and five-eighth inch diameter holes were punched in each cone in one shot.

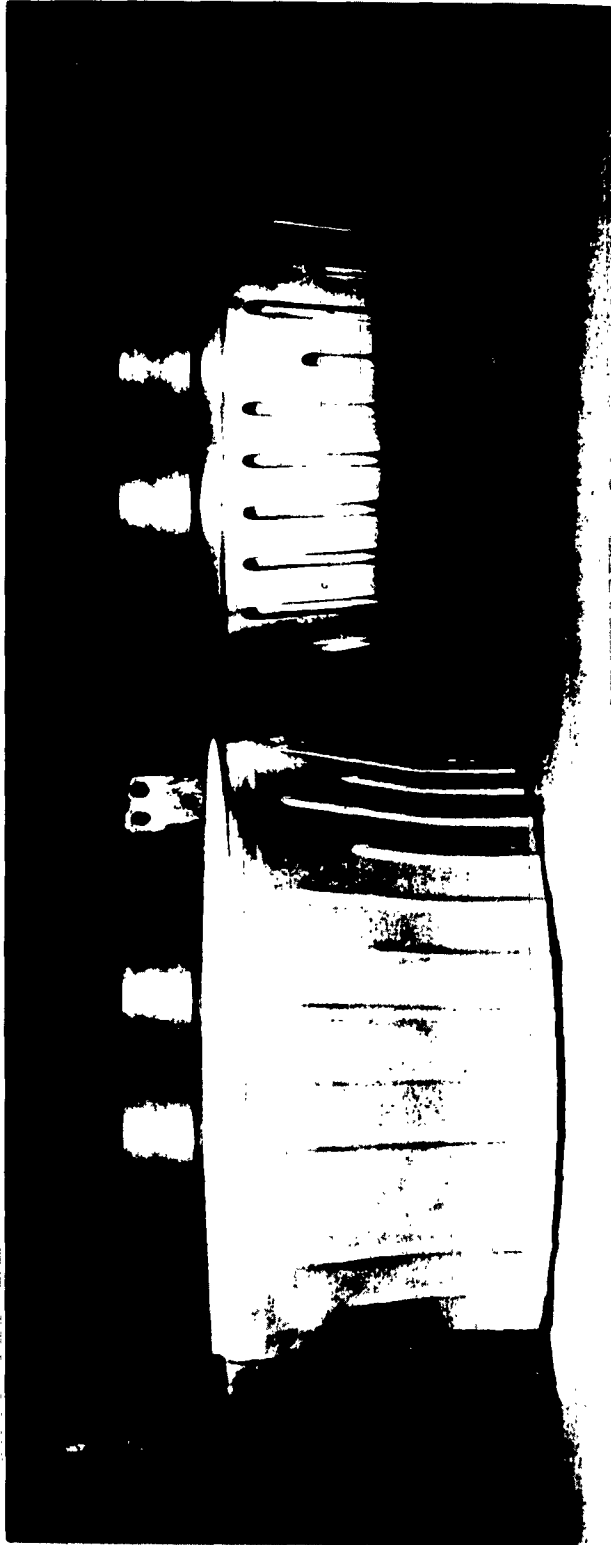
Figure 52. Courtesy of North American Aviation, Inc.



WATER SHIELD FOR ROCKET ENGINE TURBOPUMP

This part is explosively bulged from a straight 48 inch diameter cylinder of 321 stainless steel one-sixth inch thick.

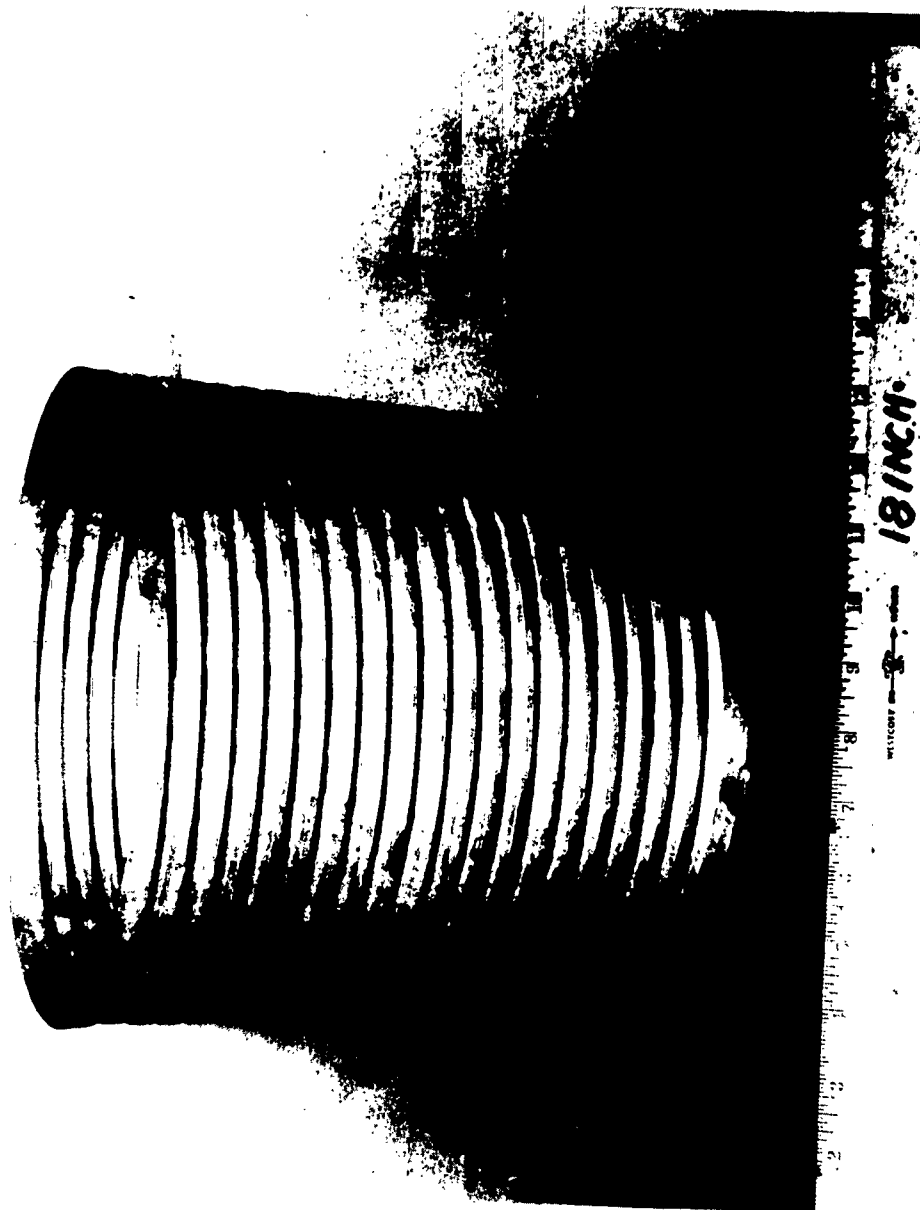
Figures 54 through 56 illustrate some of the applications developed by Pratt & Whitney Aircraft. Figure 56 illustrates another approach to sizing cylindrical parts to the final tolerances required.



PART - 451975 - FAN DISCHARGE DUCT - AMS 4027 .040 THICK.
SMD-451975-D1 FORM DIE. DEPT. 963 - EXPLOSIVE FORMING FACILITY,
P.W.A. EAST HARTFORD, CONN.

5/16/62

Figure 54. Reprinted by special permission from PRATT & WHITNEY AIRCRAFT DIVISION,
UNITED AIRCRAFT CORPORATION



PART 472879 STIFFENER - AMS 5542 NI-ALLOY .012 THICK, EXPLOSIVE
FORMED IN VACUUM TANK.

P.W.A.-H.E.R.F. FACILITY, EAST HARTFORD, CONN.

X-14511

Figure 55. Reprinted by special permission from PRATT & WHITNEY AIRCRAFT DIVISION,
UNITED AIRCRAFT CORPORATION



ATD-340, NOSE CONE I.D. SIZING DEVELOPMENT PROGRAM. SCHEME I
"BIRDCAGE" AND SHAPED CHARGE TO IMplode FLOW TURNED 6061
ALUMINUM CONES ON THE SIZING MANDREL.

X-12270

Figure 56. Reprinted by special permission from PRATT & WHITNEY AIRCRAFT
DIVISION, UNITED AIRCRAFT CORPORATION

The parts shown in Figures 57 through 59 are examples of the manner in which explosive forming can be utilized to fabricate complex configurations. These applications were developed by Ryan Aeronautical. Six hundred of the parts shown in Figure 59 were formed explosively.

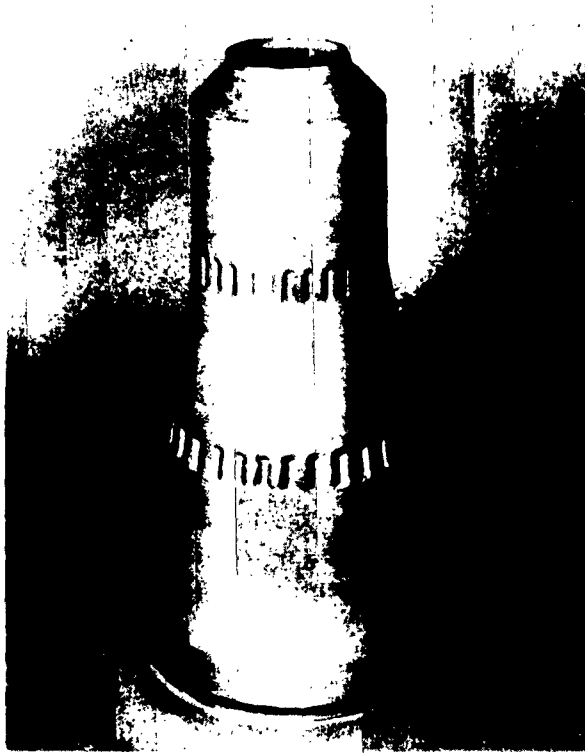


Figure 57.

Part Redesigned from 129 Details (Old Method) to One Detail by Explosive Forming

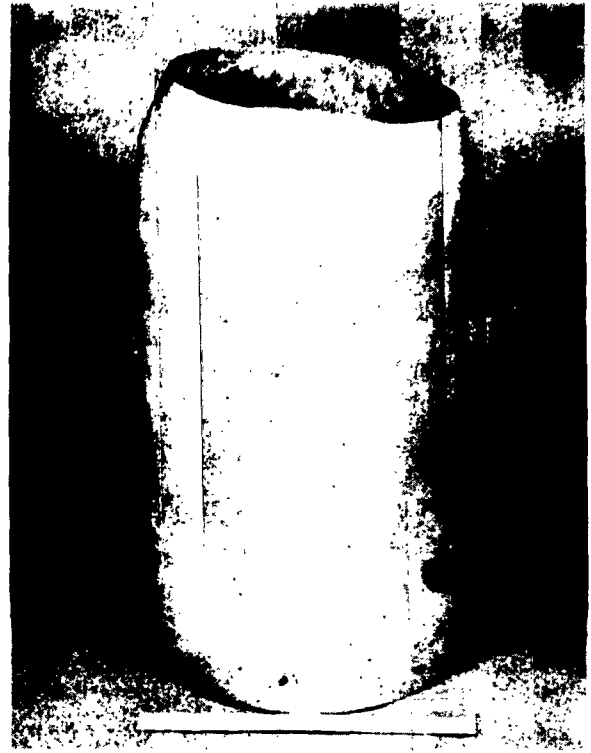
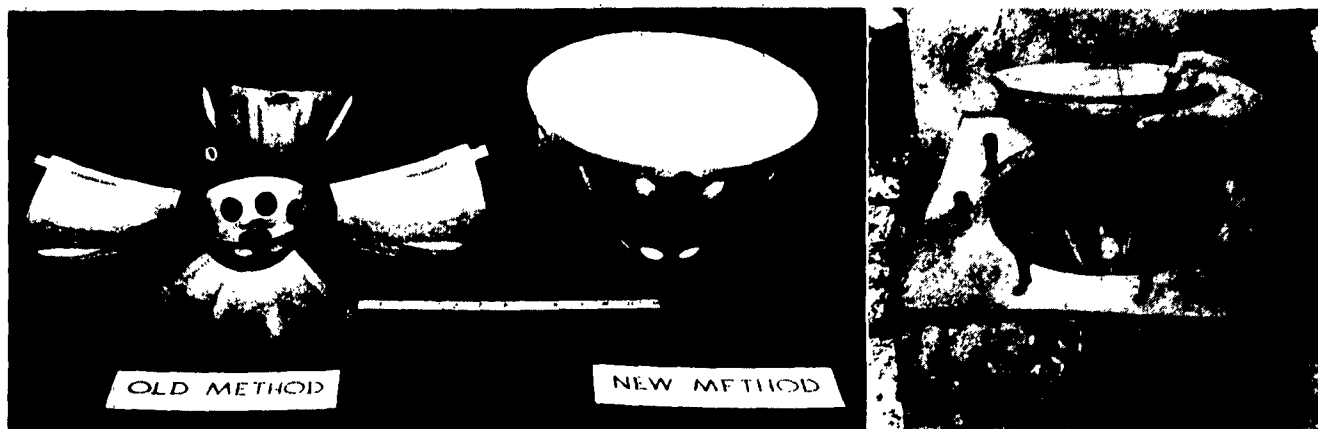


Figure 58.

Part Formerly Made in 3 Small Pieces Now Made in One Small Piece by Explosive Forming

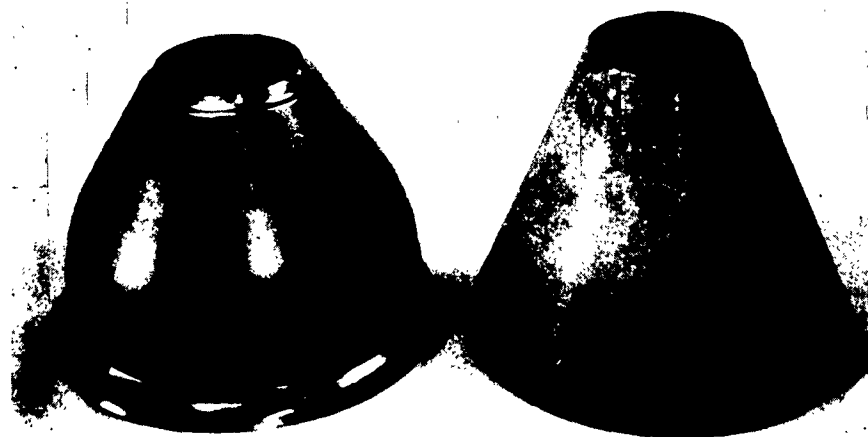
Figures 57 and 58. Reprinted by special permission from a paper by Floyd Cox, "Explosive Forming -- Research Thru Development To Production And Methods of Tooling", SP62-03, presented at a Seminar of the AMERICAN SOCIETY OF TOOL AND MANUFACTURING ENGINEERS. C 1961



This dome fits just inside the entry end of the jet engines used on the Douglas DC-8 air liner. Made from 0.040 in. thick 6061 aluminum, it used to be fabricated from five stampings that were resistance welded. Each dome cost \$131 vs. \$15 now. The job is done by rolling a cone, fusion welding the seam, and finally exploding the shape in two stages. Photo at right shows the cone blank and the die

Figure 59. Reprinted by special permission from THE PENTON PUBLISHING COMPANY from the article "Explosive Forming Goes Commercial" as published in the 14 December 1959 issue of STEEL. C 1959

The part illustrated in Figure 60 was explosively formed from a conical blank which eliminated the annealing operations required by conventional forming methods.

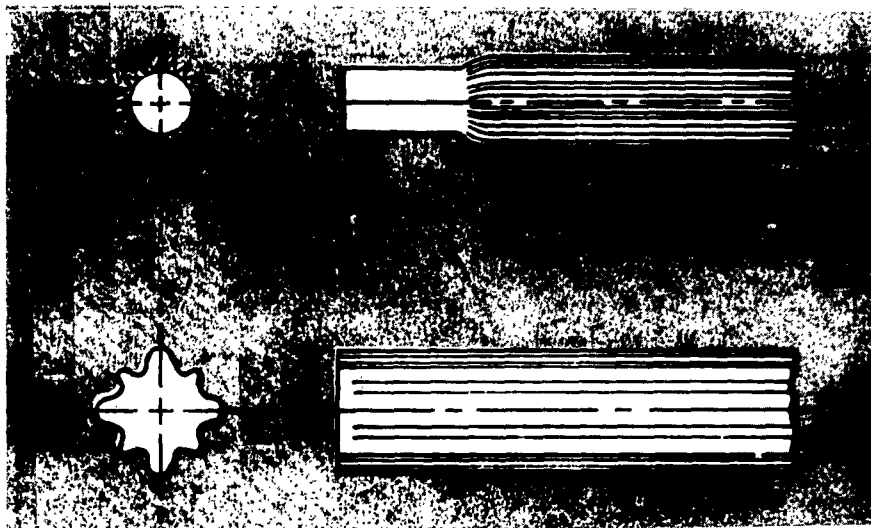


The Rene 41 diffuser cone at left used to take 10 hours to complete, including a series of process annealing steps. Now the part is explosively formed from the rolled and welded cone at right in a single blow. Total time: 15 minutes

Figure 60. Reprinted by special permission from THE PENTON PUBLISHING COMPANY from the article "Explosive Forming Goes Commercial" as published in the 14 December 1959 issue of STEEL. C 1959

The configurations shown in Figure 61 proved difficult to extrude, so North American Aviation explosively bulged tubes to achieve the final shape.

Some Alloys Resist Extrusion



NO TOLERANCE PROBLEMS: For parts which prove very difficult to extrude, due to material or shape, explosive forming serves to advantage.

Figure 61. Reprinted by special permission from CHILTON COMPANY from the article "Can Explosive Forming Solve Your Design Problems?" by E. L. Armstrong as published in the 24 November 1960 issue of THE IRON AGE. C 1960



Figure 62. This is a Symmetrical Part (a Furnace Mandrel) Which Is Difficult To Spin Because of the Material and the Very Close Tolerances Desired. It consists of two parts, the chamber (upper) section and the tail cone, each of which was formed from a pre-formed truncated cone. Made of 20 CB stainless steel 0.115 in. thick, the part is a braze mandrel used to lay up individual tubes to form a thrust chamber. Entire rig is then placed in a furnace for brazing. Reprinted by special permission from AMERICAN SOCIETY FOR METALS from the article "How to Design for Explosive Forming" by Vernon H. Monteil as published in the August 1961 issue of METAL PROGRESS. C 1961

Recent Advancements in Thrust-Chamber Fabrication Make It Mandatory to Square the Ends of the Tubes to Very Small Corner Radii (Less Than 0.005 in.). Stainless steel tubes shown in this photograph were squared and punched in one operation. The ends were severed with a cut-off wheel and then squared, punched and trimmed simultaneously. Here, the explosive techniques not only result in a well-formed tube, but eliminate a troublesome punching operation as well. These holes are consistently the same and have no appreciable burr. Material is Type 347 stainless 0.010 in. thick and the tubes are 1/4 in. square.

Reprinted by special permission from AMERICAN SOCIETY FOR METALS from the article "How to Design for Explosive Forming" by Vernon H. Monteil as published in the August 1961 issue of METAL PROGRESS. C 1961



Figure 63.



Often in Making Thin-Walled Heat Treated Assemblies, Distortion Encountered During Quenching Requires That the Part Be Formed or at Least Sized After Punching. Ordinary jigs used to prevent distortion during heat treatment are often costly and inefficient. In this aluminum part, a pylon access door, explosive techniques have been utilized to complete the forming of the part in the solution-treated condition. Furthermore, the parts produced by this method are so uniform that they are interchangeable. The alloy is 6061-T 6 aluminum, 0.063 in. thick.

Reprinted by special permission from AMERICAN SOCIETY FOR METALS from the article "How to Design for Explosive Forming" by Vernon H. Monteil as published in the August 1961 issue of METAL PROGRESS. C 1961

Figure 64.

Figure 65 below illustrates the ability of explosive forming to achieve sharper details than are obtained by conventional forming methods.

Figure 65. Engine Exhaust Transition Section for F11F Aircraft. Standard Hydraulic Press Forming and Explosive Formed Sections, Both of .025 AISI 321 Seamless Stainless Tubing, Grumman, Bethpage.

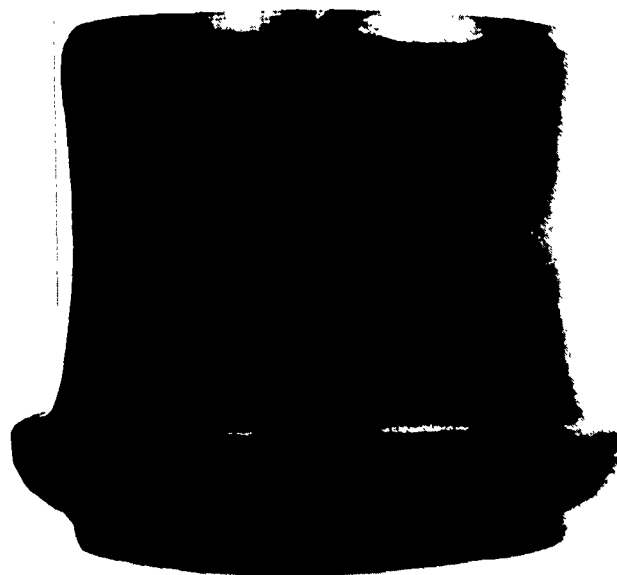
Reprinted by special permission from a paper by Vasil Philipchuk, "Explosive Forming Technology - Status of the Art", SP63-172, presented at a Seminar of the AMERICAN SOCIETY OF TOOL AND MANUFACTURING ENGINEERS. C 1963



The part shown in Figure 66 was completed (including die construction and design) in approximately three days by National-Northern (presently Flare-Northern).

Figure 66. Hub-shaped part becomes inner sleeve of afterburner on a jet engine. Blank is welded cylinder of 0.025-in. Multimet. Notice the exceptional complexity of bends at the bottom.

Reprinted by special permission from THE PENTON PUBLISHING COMPANY from the article "Explosives Blast Bottlenecks" as published in the 10 November 1958 issue of STEEL. C 1958



Figures 67 and 68 depict applications developed by DuPont. Figure 67 illustrates the normal method of sizing cylindrical or conical preform parts. The part shown in Figure 68 is another example of the capability of explosive forming to shape difficult configurations.

CYLINDRICAL SHAPES
with
SMALL LINEAR CHARGE
"PRIMACORD"

SIZING - MISSILE MOTOR CASE
10" DIA. - .050" WALL AMS-6434

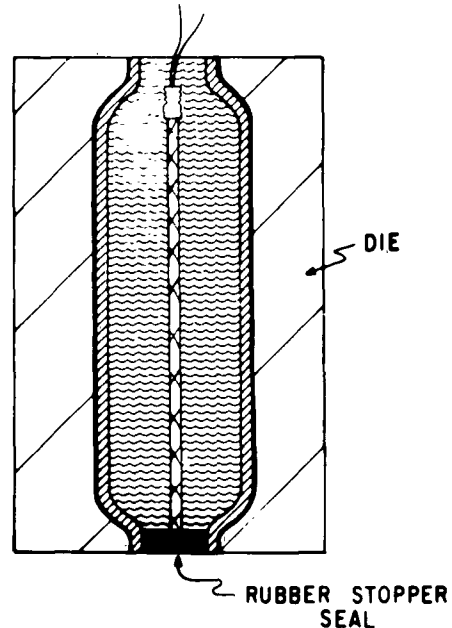


Figure 67. Courtesy of E. I. DuPont de Nemours and Company, Inc.



Plus feature of minimum springback accounts for exceptionally accurate joggle in this missile piece. Previous methods were unsuccessful

Figure 68. Reprinted by special permission from THE PENTON PUBLISHING COMPANY from the article "Du Pont Reports on Explosive Forming" as published in the 23 November 1959 issue of STEEL. C 1959

b

Figure 69 depicts an array of parts explosively formed by General Dynamics/Fort Worth.

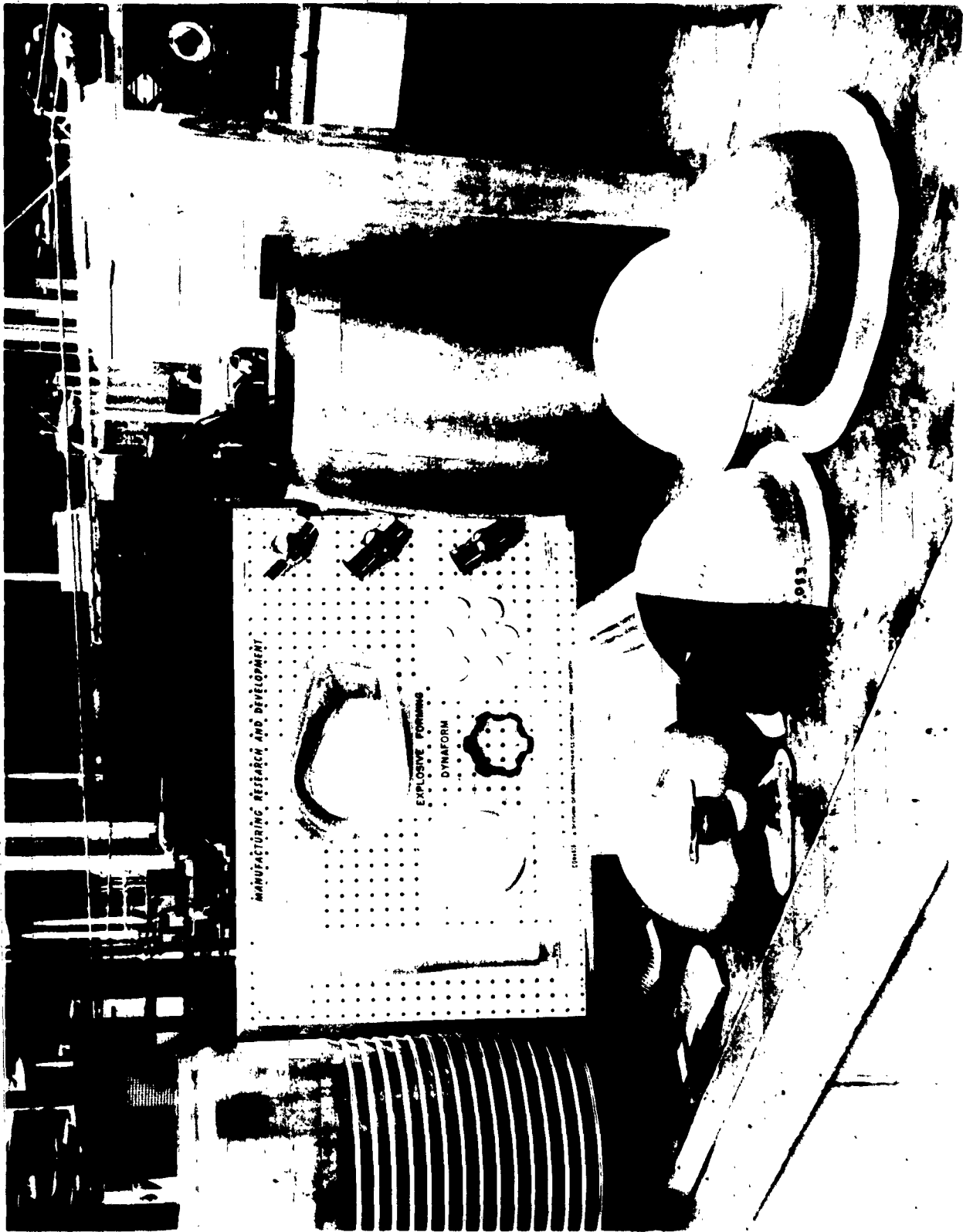


Figure 69. Courtesy of General Dynamics/Fort Worth

The part shown on the left side of Figure 70 was fabricated from three separate sections by welding. The material is 231SS .090" thick. General Dynamics/Fort Worth was able to produce this part in one piece by explosively forming a preform to the final configuration shown on the right.

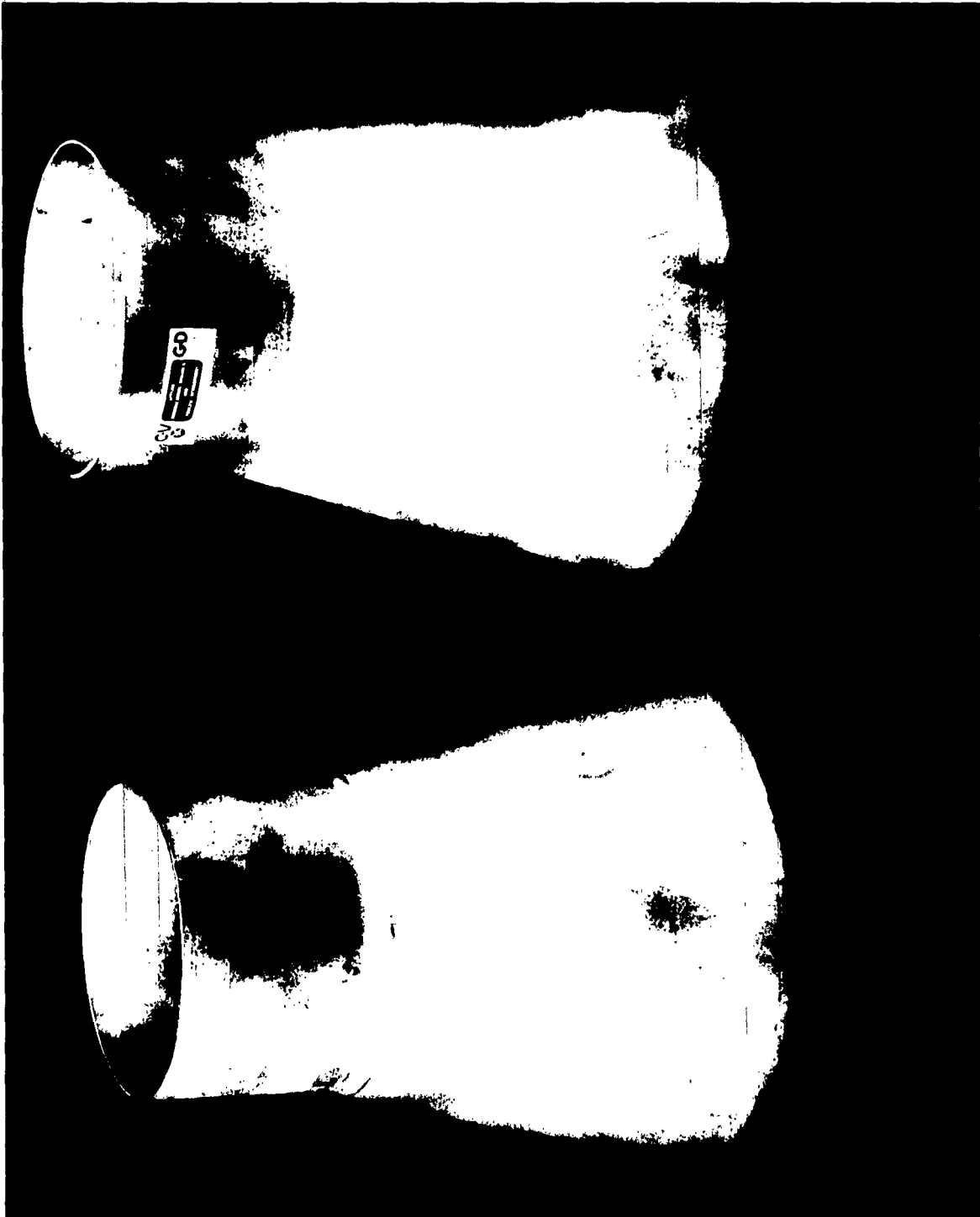
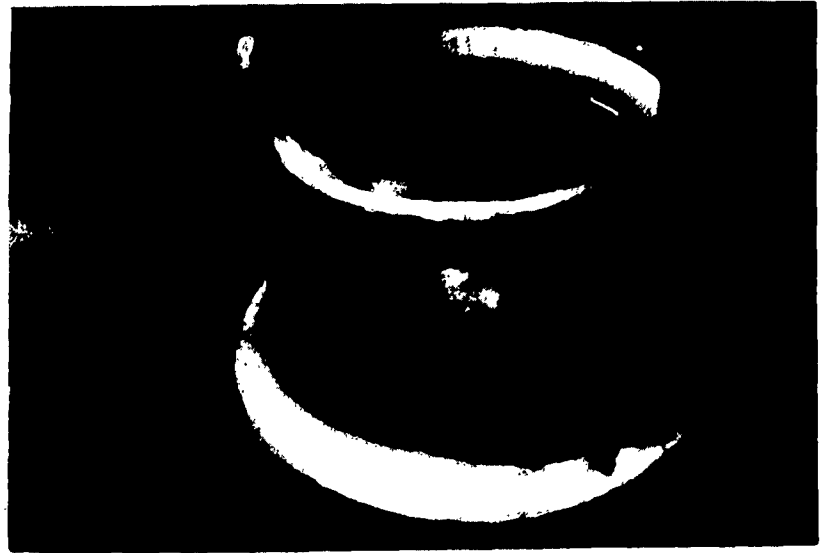


Figure 70. Courtesy of General Dynamics/Fort Worth

Figure 71 depicts a part formed by Lockheed-California at Burbank. Note the complex configuration and the relatively fine detail achieved.

Figure 71. Expanded Cone Shaped Part Tailpipe Bellmouth

Courtesy of Lockheed-California Company.

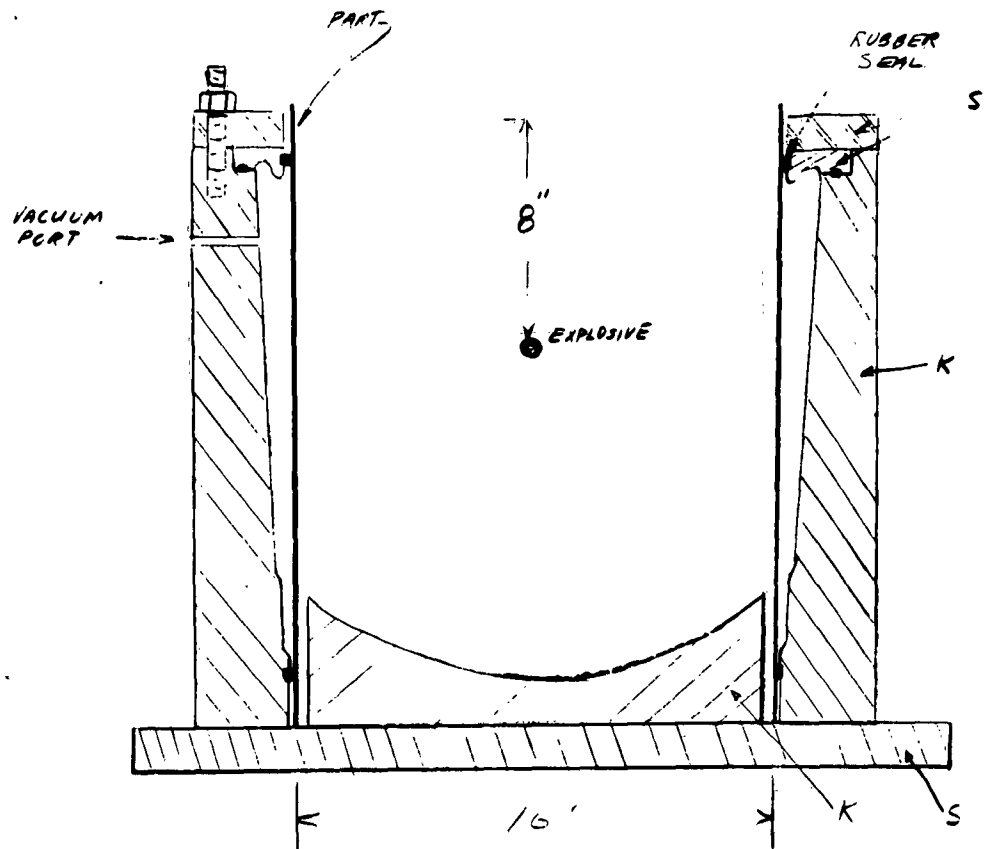


Expanded Cone Shaped Part
Tailpipe Bellmouth

The part shown in Figure 72 had the edge rolled back in the same series of operations that brought the part to its final shape. The part is made of .06" A286 material.

Figure 72. Sketch of the die, with starting blank and blast deflector in place. S = Steel
K = Kirksite

Courtesy of Ryan Aeronautical Company



The parts shown in Figures 73 and 74 were formed by NASA. The first part is constructed of 1/8" thick 7039 Aluminum.



Figure 73. Courtesy of NASA Marshall Space Flight Center

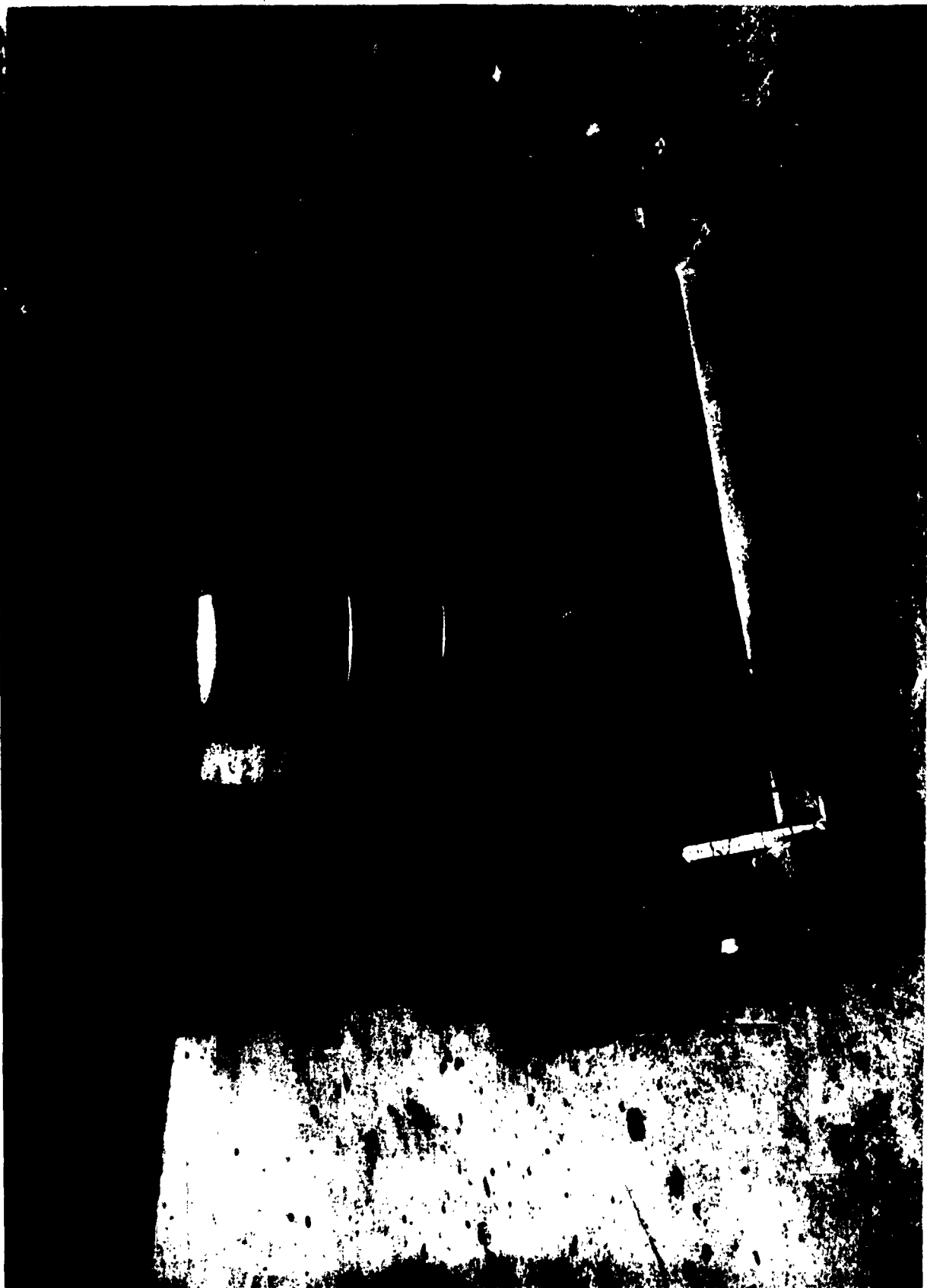


Figure 74. Courtesy of NASA Marshall Space Flight Center

In summary, parts made from cylindrical and conical blanks are generally very complex. The use of cylindrical and conical blanks is, in many cases, an attempt to overcome the limitations of either flat blank forming or conventional forming methods. The illustrations presented here are merely a representative sample of the many parts which have been formed by this technique.

(b) Flat Blank Parts: One of the highest volume of explosively-formed production parts is depicted in Figure 75 (25). Up to eighty parts per day were produced by the use of the die setup shown at the bottom of this figure. A total of 12,000 detail parts were produced. Each of the 3,000 assemblies of the configuration shown utilized four of these detail parts.

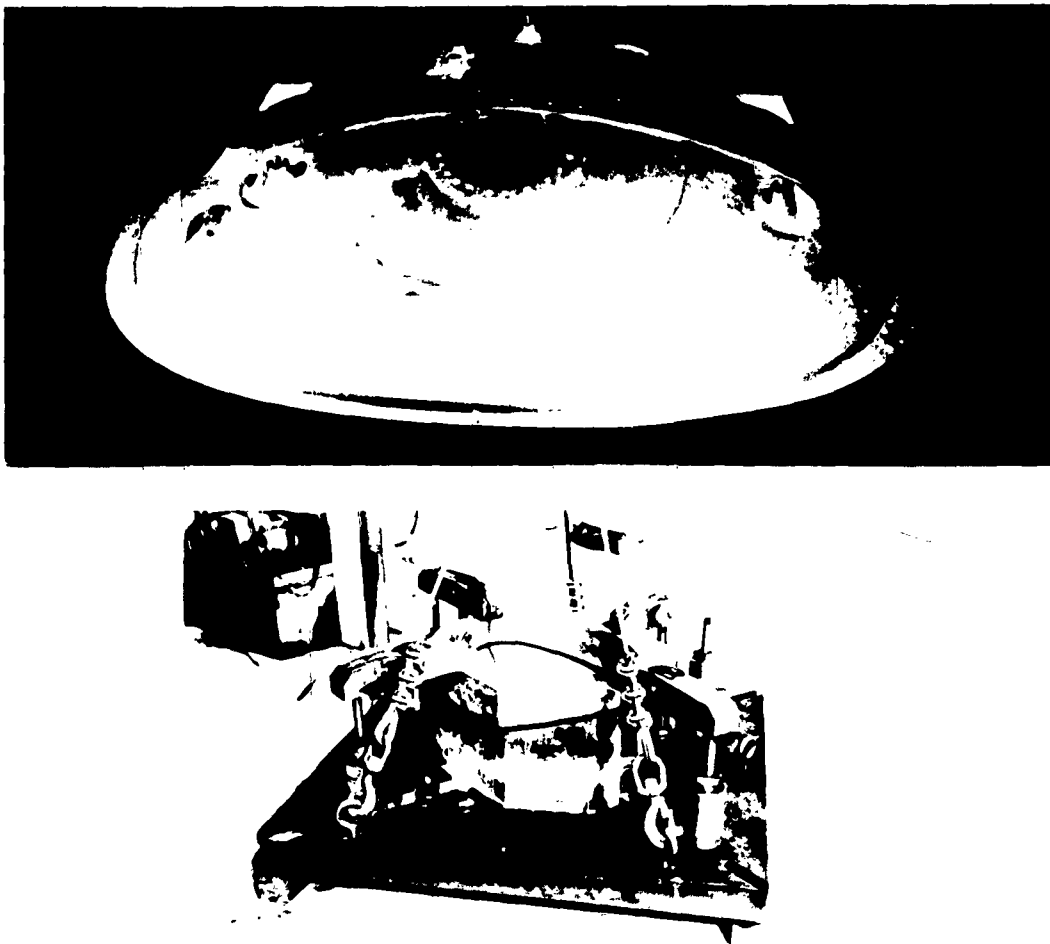


Figure 75. Airborne radar reflector made from explosively formed aluminum details spot welded together in final assembly. Forming die with fast action draw ring clamps was developed to produce hundreds of parts at rate production.

Reprinted by special permission from a paper by Lloyd Paynter, "Practical Applications of Explosive Forming" presented at a Seminar of the AMERICAN SOCIETY OF TOOL AND MANUFACTURING ENGINEERS, 9 May 1964. C 1964

b

The dome shown in Figure 76 is made of H11 tool steel. Its physical dimensions are .5" thick, 40" deep, and 156" in diameter. A truncated cone preform and an interstage anneal were used to assist in forming this part (25).

89

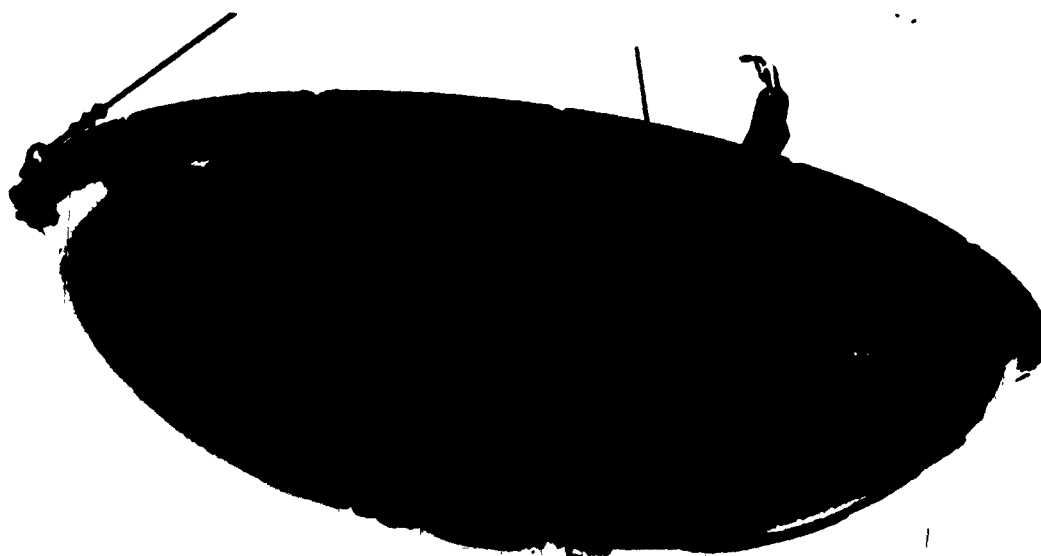
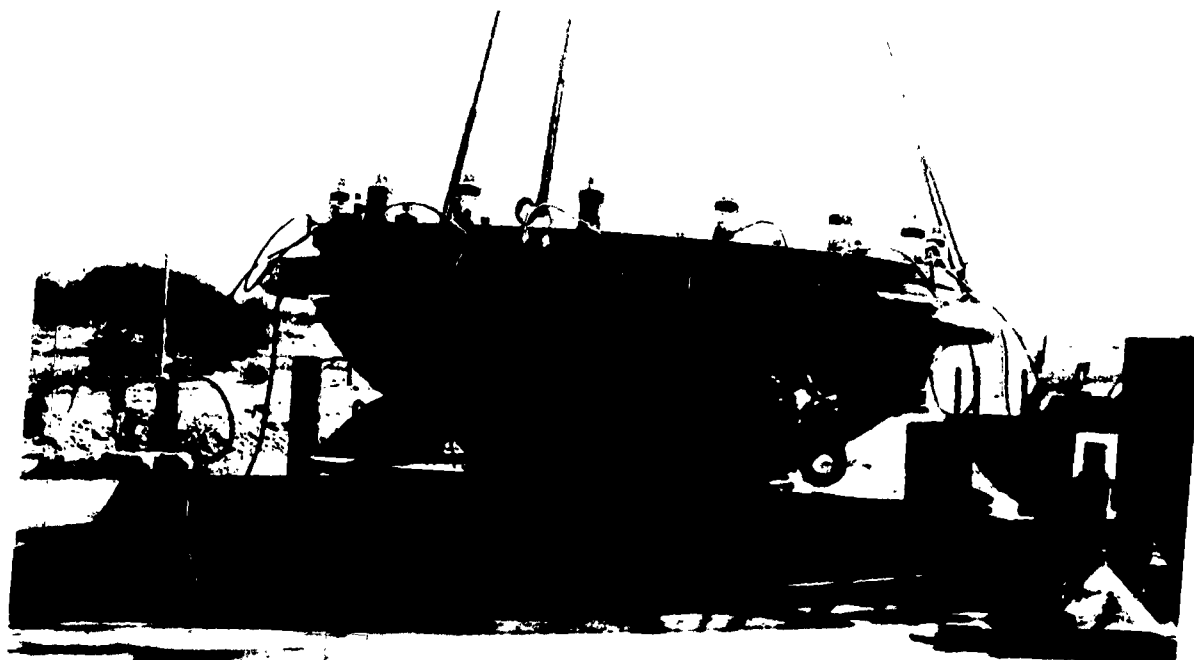
**TL**

Figure 76. Die assembly, top, and the final formed 7100-pound dome prior to trimming.

Reprinted by special permission from a paper by Lloyd Paynter, "Practical Applications of Explosive Forming" presented at a Seminar of the AMERICAN SOCIETY OF TOOL AND MANUFACTURING ENGINEERS, 9 May 1964. C 1964

The feasibility of forming welded blanks for parts which exceed standard mill sizes has been demonstrated. The weld types shown in Figure 77 give a clue as to the manner in which parts of this type should be welded prior to forming.

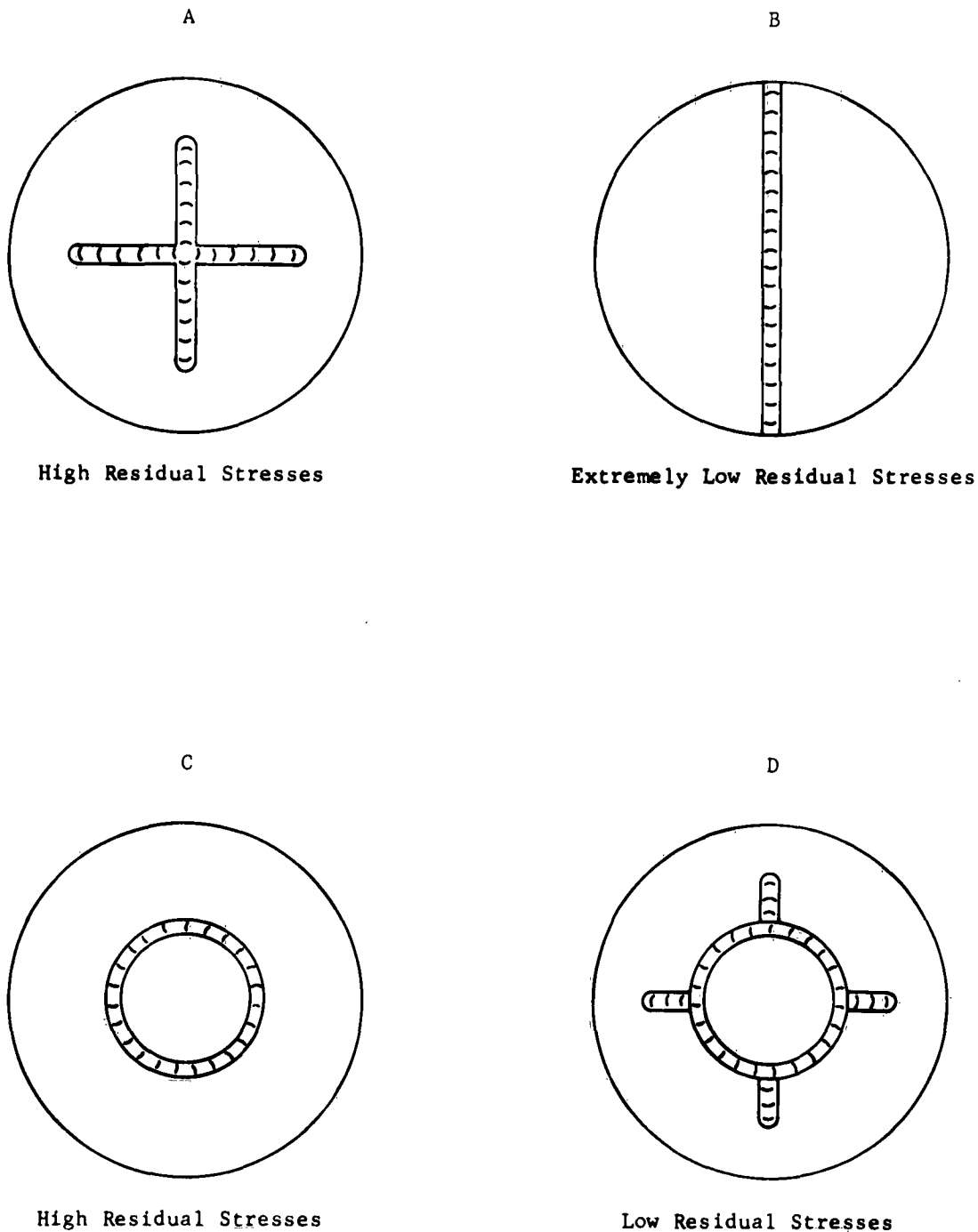
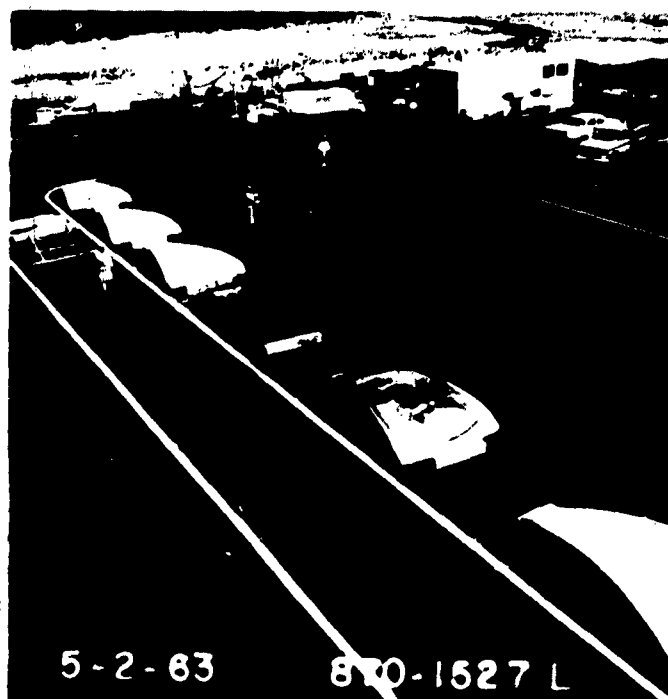


Figure 77 Weld Configurations Investigated for Explosive-Forming Response

Reprinted by special permission from MARTIN MARIETTA CORPORATION from Report IR-62-6 titled, "Determination of Formability Limits for 2014 Aluminum Alloy When Explosively Formed".

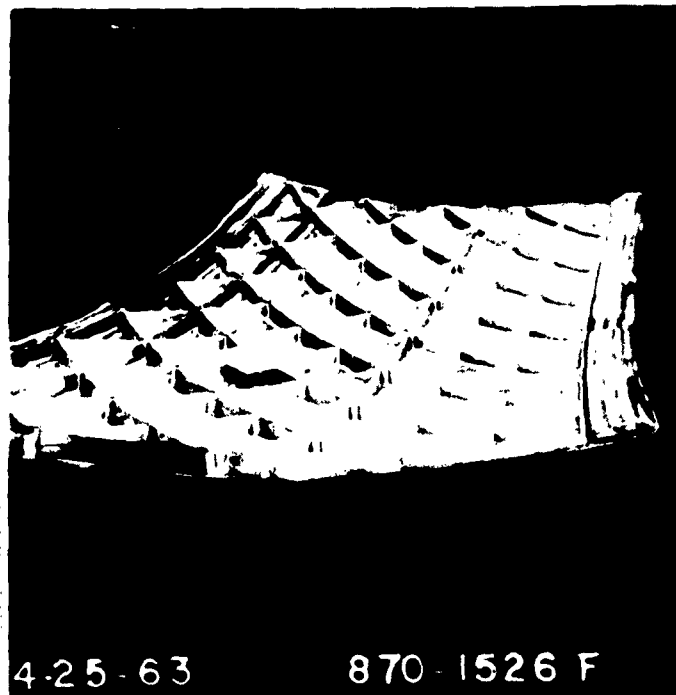
The parts shown in Figures 78 through 80 were formed by North American Aviation.



GORE PANELS FOR SATURN S-II BULKHEADS

These gore sections are formed from flat sheets of 2014 aluminum. Four different types of gores are formed in one-eighth, three-sixteenth, one-quarter, and one-half inch thicknesses. The smallest gore is 15 feet long by 10 feet wide, and the largest gore is 20 feet long by 10 feet wide. Over 350 of these gores have been formed to date.

Figure 78. Courtesy of North American Aviation, Inc.



WAFFLE PANEL FOR SATURN S-II BULKHEADS

The panels are machined from 2014-T4 aluminum in the flat condition and then formed to the configuration shown. The panels are 76 inches by 96 inches by one and one-half inches thick. Over 100 of these waffles have been formed to date.

Figure 79. Courtesy of North American Aviation, Inc.



STIFFENER PANEL FOR THE B-70 BOMBER

This beaded part is formed in one shot from a flat sheet of 0.050 inch thick PH 15-7 Mo.

The part shown in Figure 81 is about 9' in diameter and .19" thick. Three of these parts were made on a kirksite die. The material is aluminum.

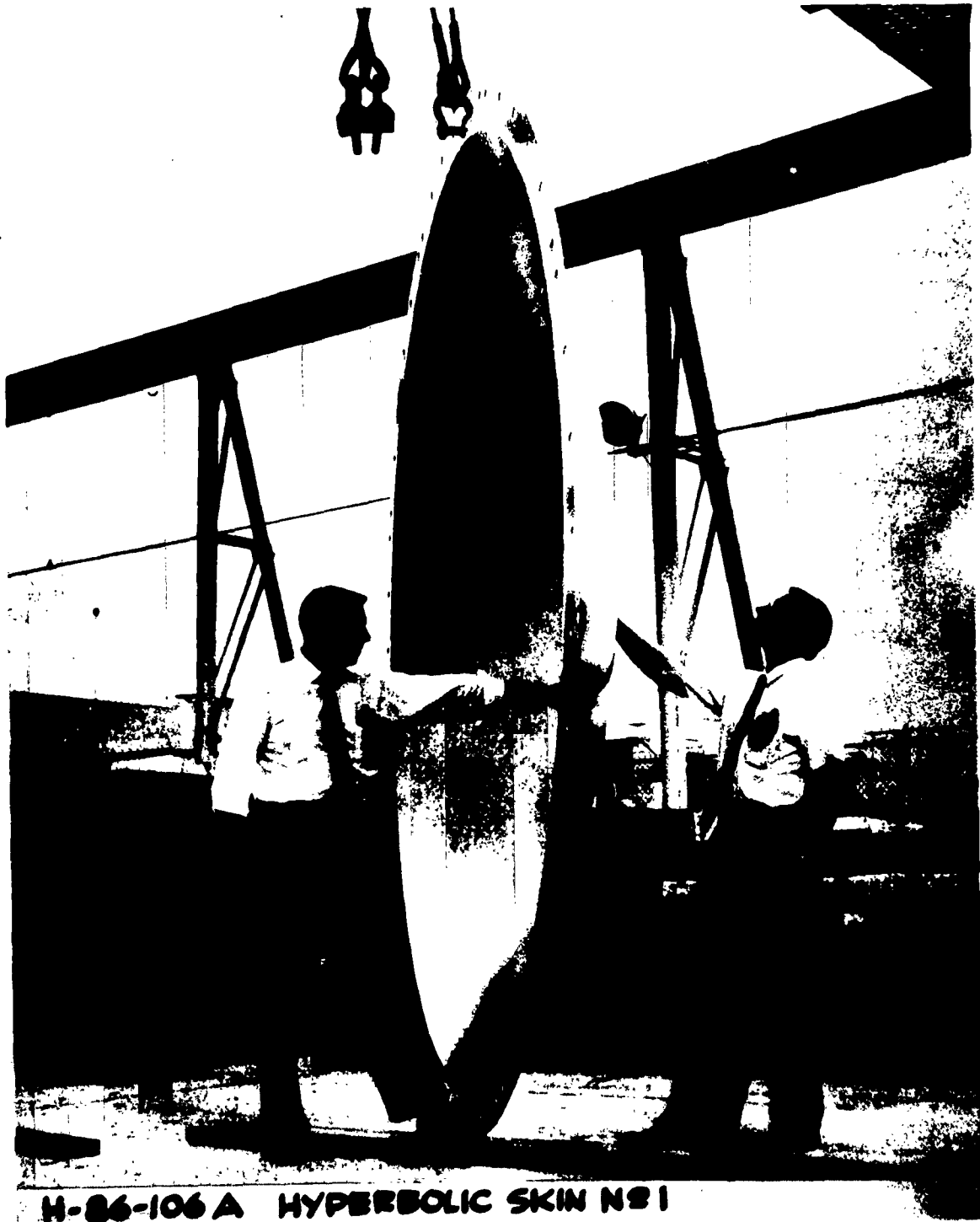


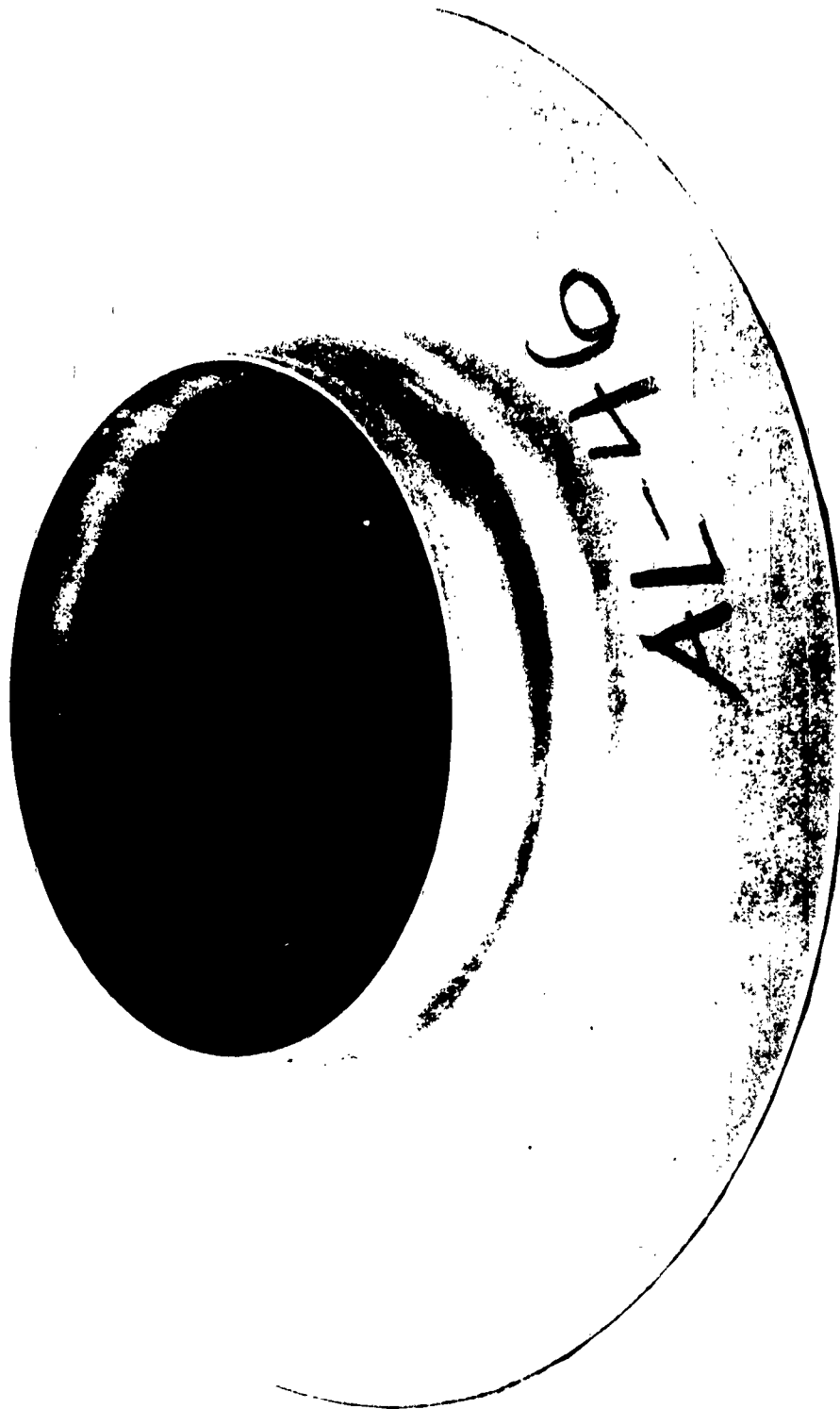
Figure 81. Reprinted by special permission from NORTH AMERICAN AVIATION, INC., from Report No. MEP 8006

The cost data associated with the part shown in Figure 81 is listed in Table 15. It is estimated that the cost of matched dies of the same material for a conventional press would be approximately twice the cost of the explosive forming die. As can be seen, the cost of the explosive is a minor part of the total cost.

The purchase of single heat of aluminum for three special skins .190 x 136 x 136	\$1750.00
250 feet of explosive @ 4.8¢/ft.	9.84
12 detonating caps @ 83¢ each	9.96
Misc. expense (wire, tape, etc.)	5.00
Production labor - 42 hours @ \$6.10	256.20
DIE COST	
Kirk site - 21,000 lbs. @ 11¢/lb.	\$2310.00
Labor to cast and finish die - 485 hours @ \$6.10	\$2958.50
Machining cost	<u>\$2150.00</u>
TOTAL	\$9449.50

Table 15. Reprinted by special permission from NORTH AMERICAN AVIATION, INC., from Report No. MEP 8006.

The part illustrated in Figure 82 illustrates the use of this technique to produce flanged parts.



H-96-156 D 6-6-60

Figure 22. Reprinted by special permission from NORTH AMERICAN AVIATION, INC., from Report No. MEP 8006

The parts shown in Figure 83 illustrate the usage of scaling laws to develop the full scale forming parameters on a scaled down part.



Figure 83. Courtesy of Martin Company

The aluminum part shown in Figure 84 is the engine inlet nose cone for the 727 airplane. It was formed by Boeing at Wichita.

Figure 84. Explosive Coining Operation produces smooth-surfaced cowl ring to within ± 0.030 in. of specified size in 45-min. average floor-to-floor time, using steel "spanking" die with water tank.

Reprinted by special permission from McGRAW-HILL PUBLISHING COMPANY, INC., from the article "Explosive Coining of Engine Cowls" by Robert W. Lightstone as published in the 28 October 1963 issue of AMERICAN MACHINIST/METALWORKING MANUFACTURING. C 1963



The wheel cover depicted in Figure 85 illustrates the fine detail which can be achieved with the explosive forming method.

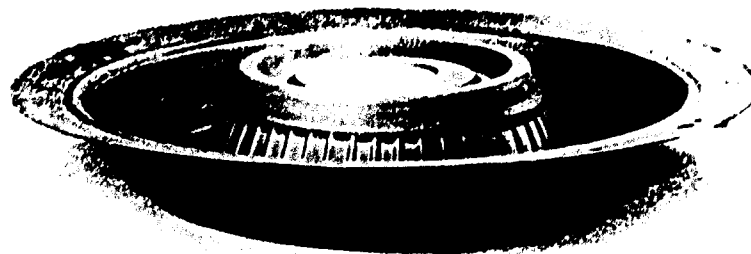


Figure 85. Courtesy of Martin Company

The applications shown in figures 86 and 87 were developed by the Boeing Company of Seattle, Washington.



2A13K265

TREAT- 125-208-0 ALUMINUM
EXTRUSION FORMED TO COMPOUND
CONTOUR 3-1-63

Formed skin showing compound contour

Size: 48 x 144 inch 0.125 2024-0 aluminum

Figure 86. Courtesy of Boeing/Seattle

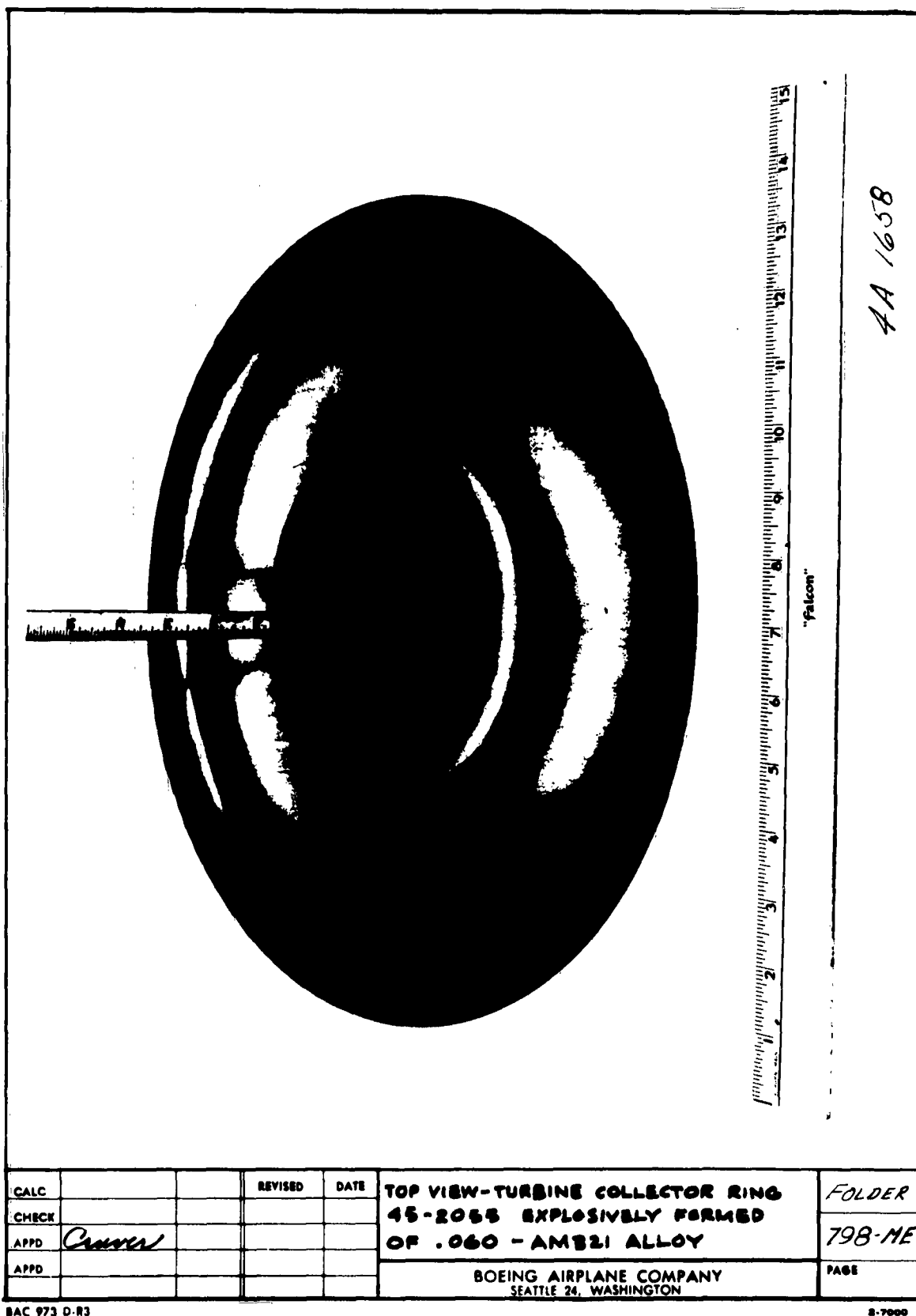


Figure 87. Courtesy of Boeing/Seattle

b

Figure 88 depicts a part which had been bulge formed and then explosively sized to the final tolerances required.



Explosively sized part after being removed from die

Figure 88. Courtesy of Boeing/Seattle

The manifold section shown in Figure 89 was formed by North American Aviation. Note the material.

Figure 89. Manifold section about 4-1/2 feet in diameter, made from Rene' 41 for use on a rocket engine.

Reprinted by special permission from Industrial Press from the November 1960 issue of MACHINERY.
C 1960

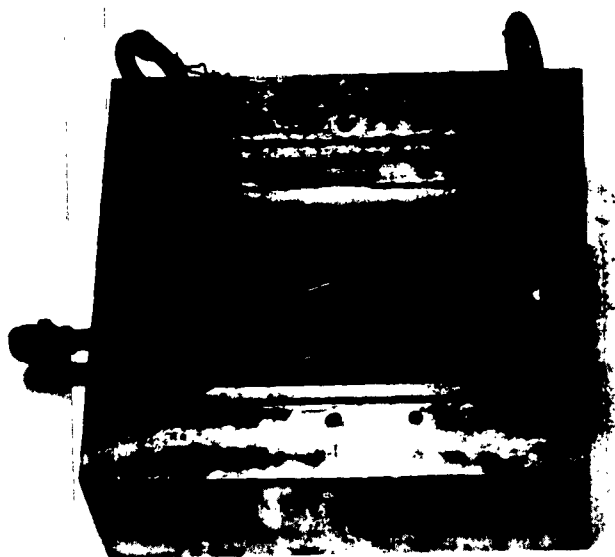


Figures 90 and 91 illustrate the ability of explosives to pierce flat blank parts. The part shown in Figure 91 was both formed and pierced in the same operation. This type of application is ideal for this method.



Figure 90. Large sheet of Hastelloy X through which a variety of holes was pierced by blowing the surrounding "punches" through the sheet.

Reprinted by special permission from THE INDUSTRIAL PRESS from the article "Ryan's Split-Second Explosive Forming" by Charles O. Herb as published in the July 1959 issue of MACHINERY.
© 1959



ATD-1918 DIE INSERT AND HOLDER USED IN DEVELOPMENT PROGRAM TO FORM AND PIERCE .015 WASPALLOY SHEET USING HIGH ENERGY EXPLOSIVES.

11/24/61

Figure 91. Reprinted by special permission from PRATT & WHITNEY AIRCRAFT DIVISION, UNITED AIRCRAFT CORPORATION

The parts shown in Figure 92 represent a unique solution to the problem of forming honeycomb sections. The Martin Company has stated that the explosive forming method has yielded excellent results on this type of part. Note the thickness of the parts.

NASA-CR-64-36



(a) Cup Segment



(b) Type I Upper Gore



(c) Type II Lower Gore

Face Plate - 0.250-in.-Thick 2014-T6 Aluminum Alloy
Core - 2.0-in.-HRP Phenolic Honeycomb Core

Figure 92. Courtesy of Martin Company

The following series of figures are grouped in this manner so as to concentrate the activity in forming relatively thick parts. Of primary interest is the dimensional similarity between these parts and the armor currently used by the U. S. Army.



Figure 93. ONE AND ONE-HALF INCH ELLIPTICAL TANK END

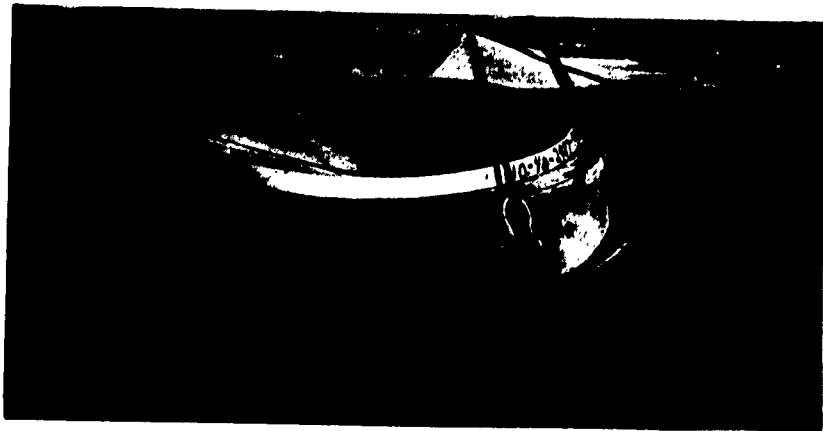
This tank end (shown untrimmed) was formed from a flat sheet of one and one-half inch thick 1020 steel.



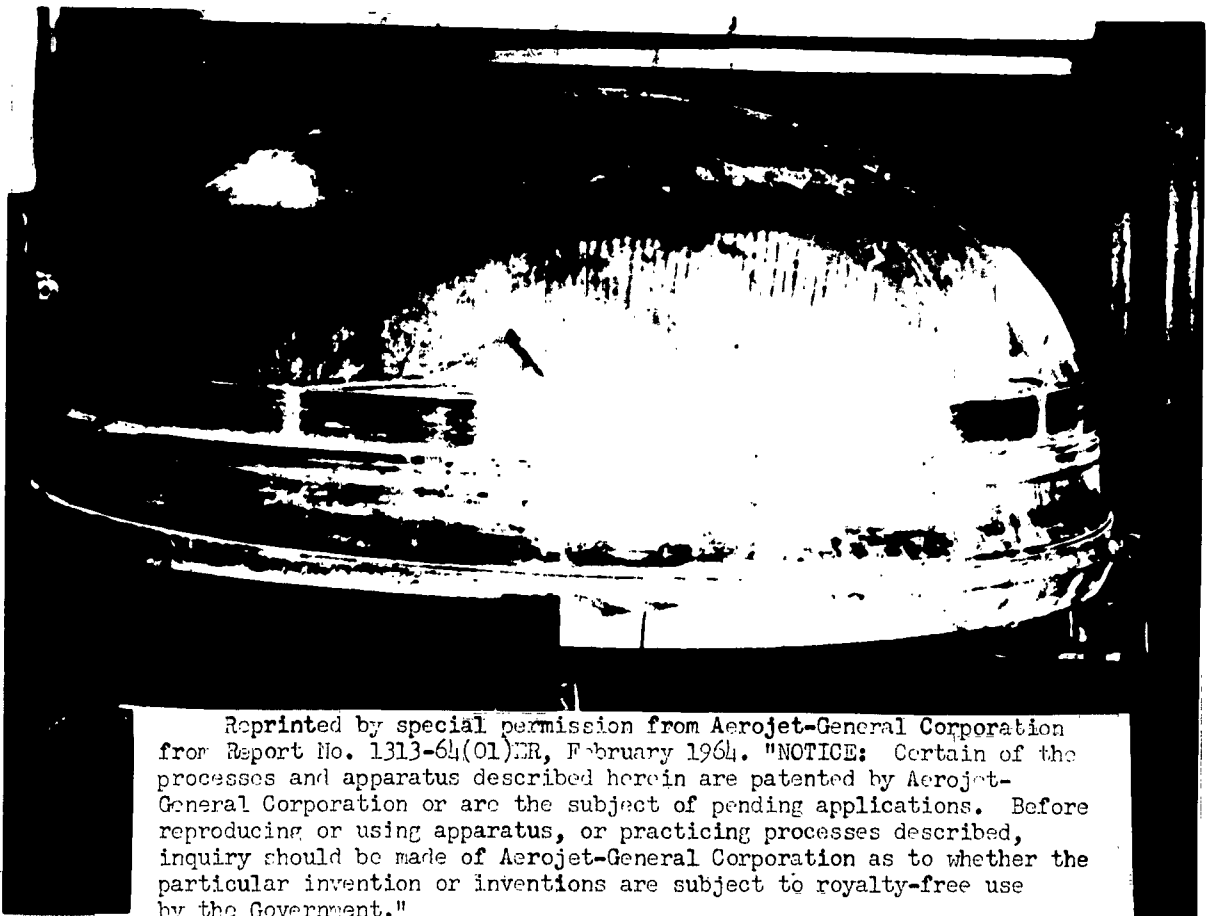
Figure 94. Although this Aluminum Hatch Cover Is Small (24 In. in Diameter), It Represents a Type of Forming Which Usually Requires Large Equipment. With the tremendous forces available in explosives, such operations are quite inexpensive and feasible. This part was made from 6061-T 6 flat stock $1\frac{1}{2}$ in. thick.

Reprinted by special permission from AMERICAN SOCIETY FOR METALS from the article "How to Design for Explosive Forming" by Vernon H. Monteil as published in the August 1961 issue of METAL PROGRESS. C 1961

Figure 95. Aluminum armor plate 4 in. thick takes a 24 in. dishing with explosive forming setup. Hardness increases, too. Reprinted by special permission from THE PENTON PUBLISHING COMPANY from the article "Machines Turn



Violence Into Forming Profits" as published in the 6 August 1962 issue of STEEL. C 1962



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Figure 96. Aluminum Dome (4 in. Thick, 54 in. in Diameter) Explosively Formed From a Flat Blank. (Weight is approximately 1 ton.)



Figure 97. Torus Section 54 in. in Diameter Explosively Formed from
1-in. - Thick Stainless Steel.

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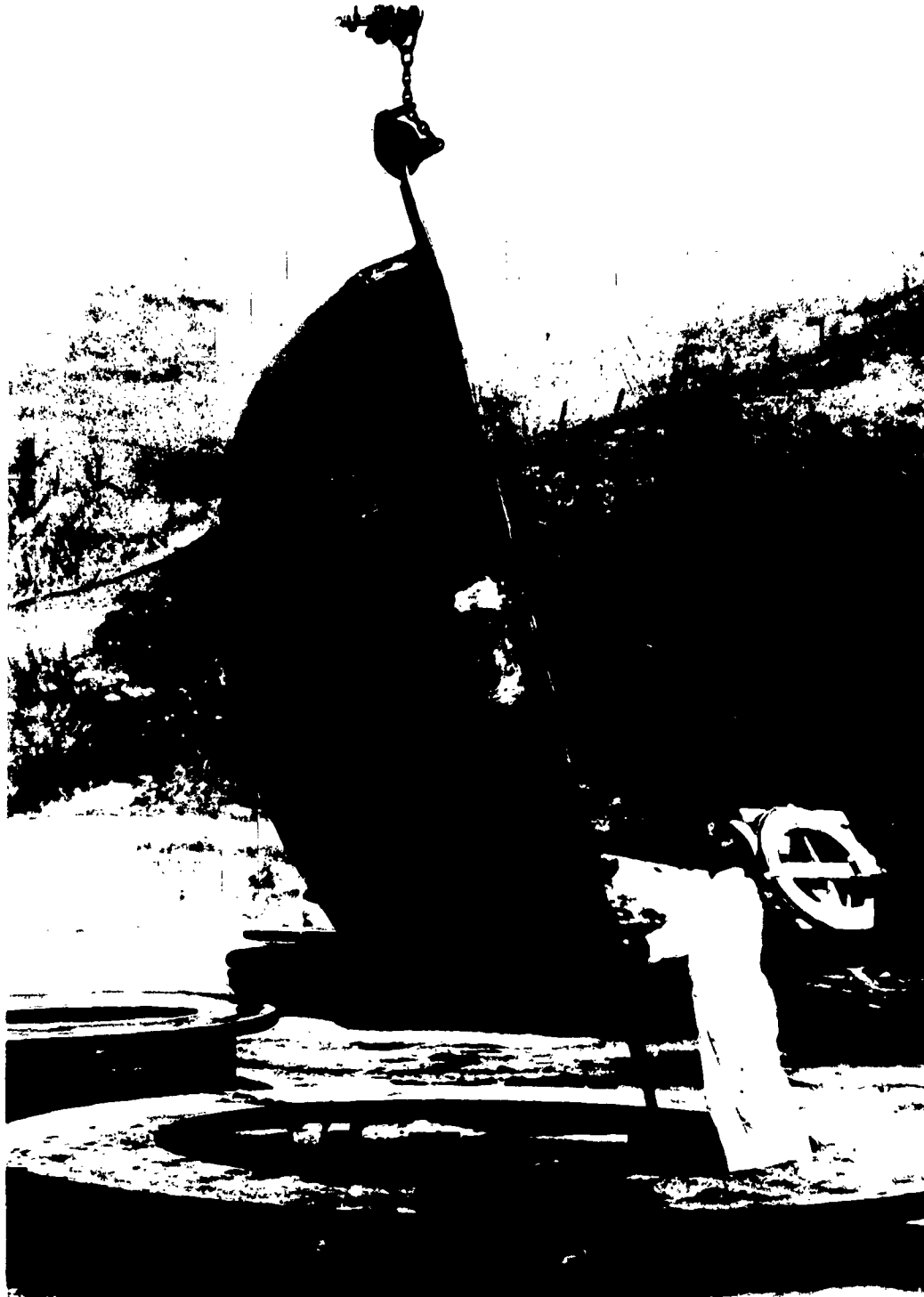
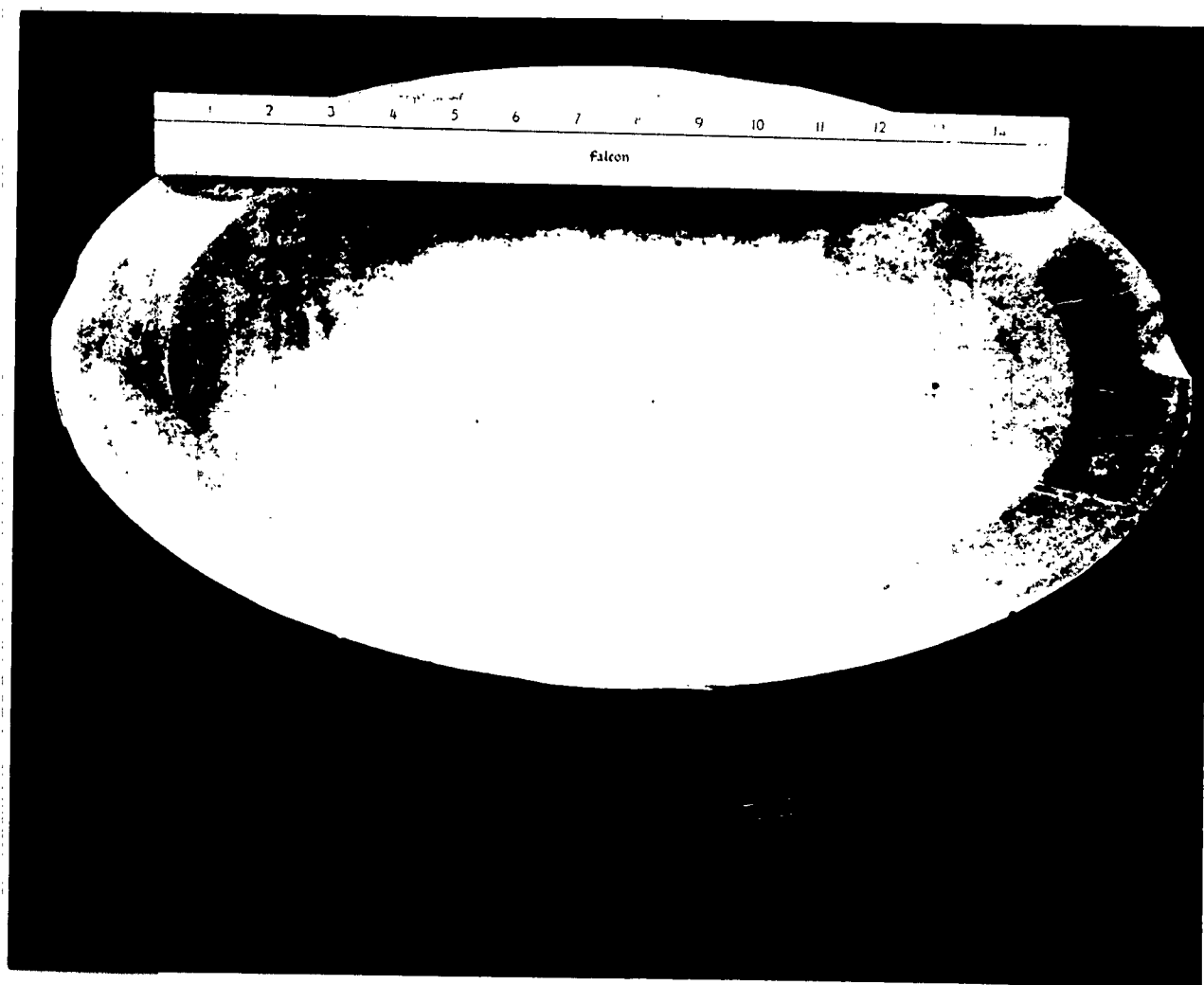


**Figure 98. Elliptical Dome, 120 in. in Diameter and 1/2 in. Thick,
Explosively Formed from 1/2-in. -Thick Flat Steel
Sheet. (Approximate weight is 2 tons.)**

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Formed hemisphere, 17 inch diameter, 1-1/2 inch 2024-O aluminum

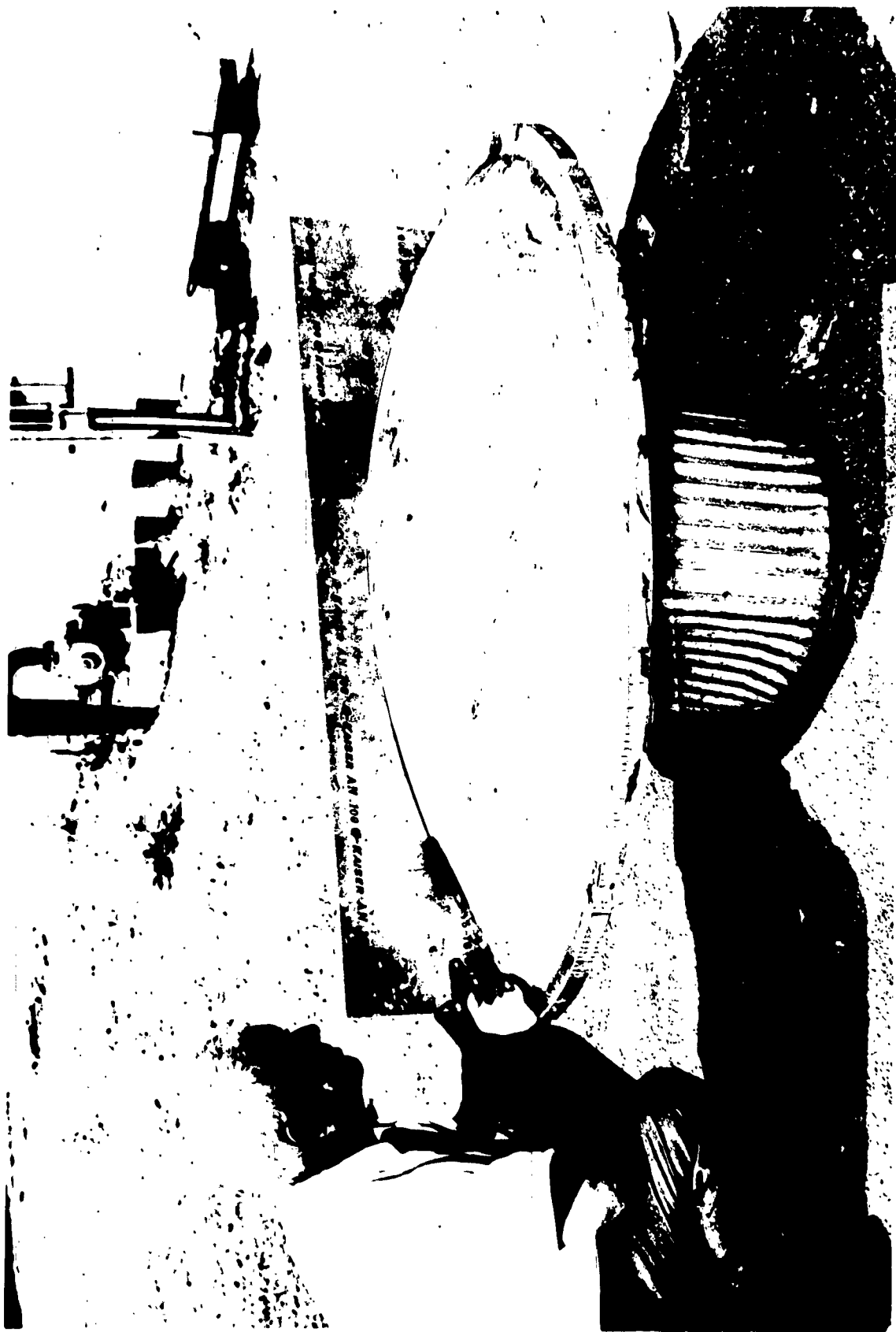
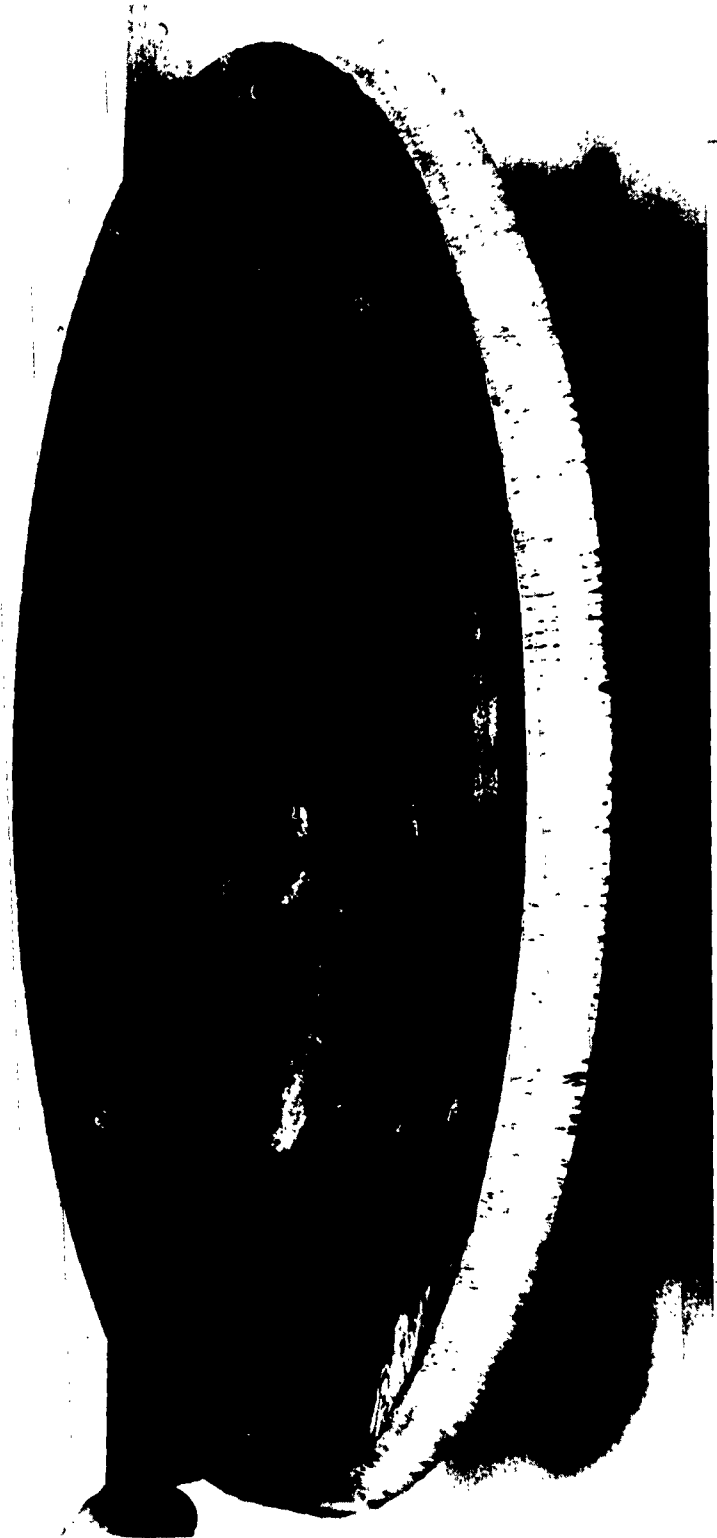


Figure 100. CONTOUR CHECK TEST PART NUMBER THREE (EXPLOSIVELY
STRETCH FORMED 2219-T37 .500 INCH THICK)

Courtesy of NASA Marshall Space Flight Center

The part shown in Figure 101 is 1-1/4" thick 7075 aluminum. It is machined at huge material and time savings to the configuration shown in Figure 102.



"Courtesy of Fort Worth Division, General Dynamics Corp."

Figure 101. Courtesy of General Dynamics/Fort Worth

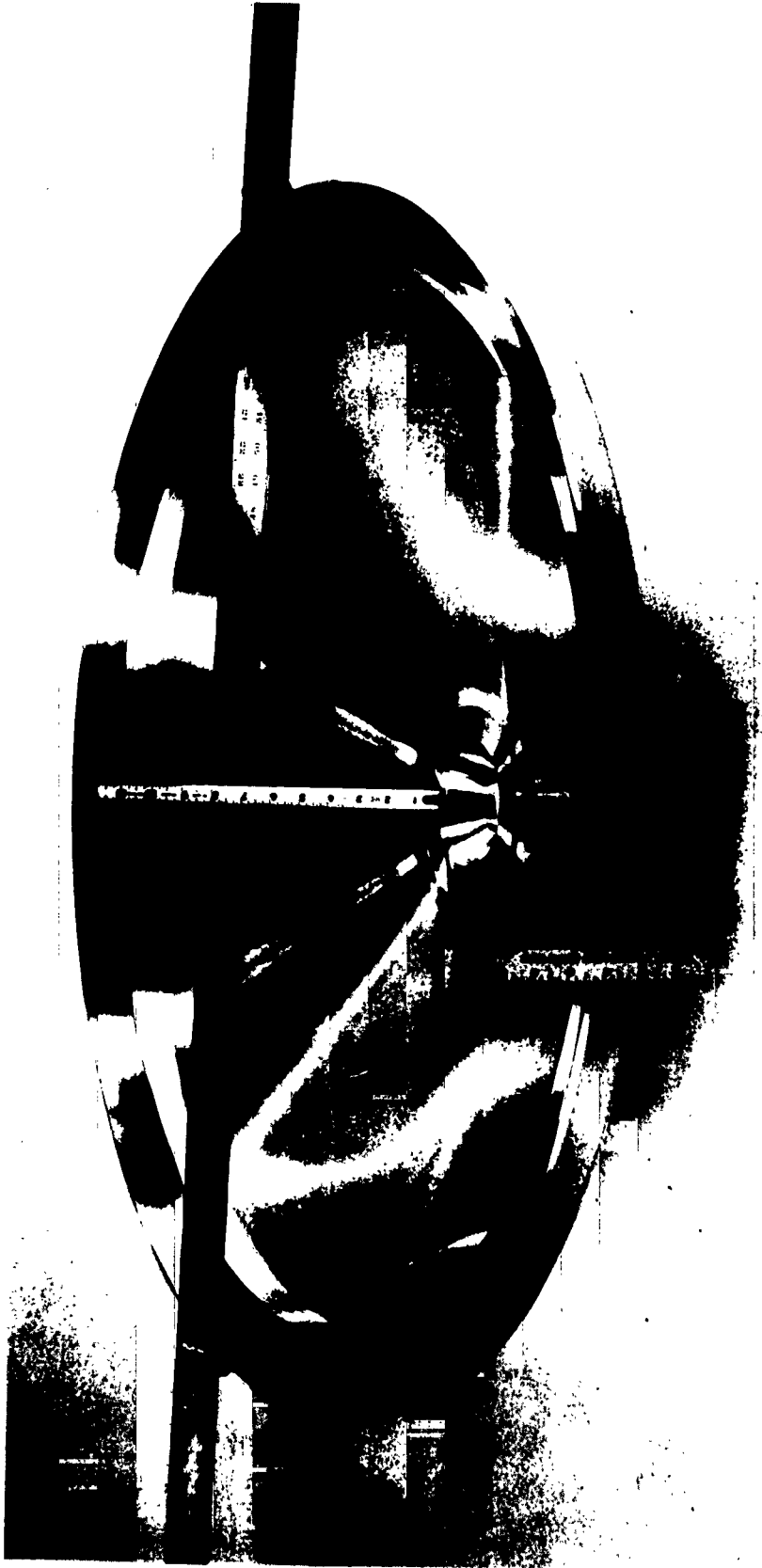


Figure 102. Courtesy of General Dynamics/Fort Worth

The domes shown in Figure 103 are $5/8$ " thick, 10' diameter 2014 aluminum. Note the steel-backed, epoxy-faced concrete die in the background.



"Courtesy of Martin Co., Denver, Colorado."

Figure 103. Courtesy of Martin Company

(c) U. S. Army Activity: Aerojet-General at Downey, California has stated that they have formed 1-1/2" thick 5083 aluminum and retained the ballistic characteristics of the material (4). They also have stated that they have formed shallow-dish 5000 series aluminum parts which were 2" thick. They stated that 200 of these parts may be produced for a classified military project (58). Interest in the use of this method to form armor sections has been demonstrated by the U. S. Army Tank-Automotive Center as is evidenced by their PEMA project. It is hoped that the results of this project will be widely disseminated so that future vehicles will incorporate any advantages which arise from this project.

The Ordnance Division of Minneapolis-Honeywell conducted a study of the manufacturing methods which could be used on the Honest John, Lacrosse, Littlejohn, and Sargeant Missile Skins. The following uses for explosive sizing were listed (43):

Littlejohn, AAL-LJ "B" Section

Littlejohn, T54 "B" Section
"C" Section

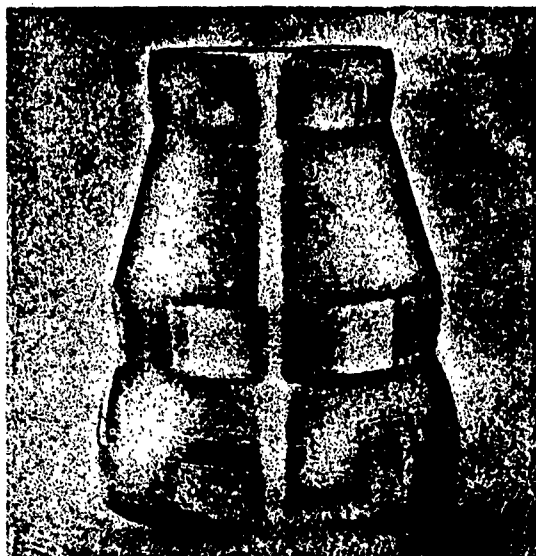
Sargeant, T53 "B" Section
"C" Section

Honest John, XM86 "B" Section

Sargeant, XM91 "B" Section

Cognizance must be taken of the fact that these applications were developed in 1959. However, this information does indicate the potential application of explosive sizing to this type of part configuration.

Figure 104 depicts a gas seal which was formed by Grumman Aircraft. Table 16 lists the operations required by both conventional and explosive forming methods for this part. It would appear that this application was a fairly successful one.



GAS SEAL FOR 20MM CANNON

Finished Dimensions: Length - 3.583"
 Max O.D. - 3.00"
 Min O.D. - 1.927
 Thickness - (.065 nominal)

Material: 321 Stainless Steel - Annealed

Figure 104. This part was formed from seamless tubing using a high explosive and an axially split steel die. One operation was sufficient to form the piece and no vacuum was required.

Figure 104 and Table 16 are reprinted by special permission from a paper by Arthur Wickesser, Jr., "Recent Developments in Explosive Forming at Grumman Aircraft", No. 229, (C) 1959, presented at a Seminar of the AMERICAN SOCIETY OF TOOL AND MANUFACTURING ENGINEERS

Table 16

Operation Sheet for Forming 20 MM Gun Seal

Conventional Forming	Explosive Forming
1. Saw tubing	1. Saw tubing
2. Deburr	2. Deburr
3. Degrease	3. Degrease
4. Bulge (rubber)	4. Bulge (explosive)
5. Anneal	5. Machine
6. Bulge (rubber)	6. Inspect
7. Anneal	
8. Bulge	
9. Machine	
10. Inspect	

Both methods of forming require approximately the same amount of setup time for one bulge operation.

Cannon bore evacuators have historically been a source of fabrication problems. Figures 105 through 108 depict the work that has been performed by various contractors. It should be noted that stainless steel is not an acceptable material.



Figure 105. Bore evacuator chamber explosively formed in a closed die. Material is .440 thick stainless steel. Part is shown prior to welding and machining operations.

Reprinted by special permission from a paper by Lloyd Paynter, "Practical Applications of Explosive Forming" presented at a Seminar of the AMERICAN SOCIETY OF TOOL AND MANUFACTURING ENGINEERS, 9 May 1964. © 1964

EXPLOSIVE FORMING
ECCENTRICALLY BULGED TUBE
8740 STEEL - 3/8 IN. WALL

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Figure 106. Courtesy of E. I. DuPont de Nemours and Company, Inc.



GUN BARREL BORE EVACUATOR

This part is explosively bulged from a
straight 7 inch diameter x three-eighth
inch wall thickness steel pipe.

Figure 107. Courtesy of North American Aviation, Inc.

EXPLOSIVE FORMING WATERVLIET ARSENAL DEVELOPMENT CONTRACTS

ITEM	MATERIAL AND WALL THICKNESS	CIRCUMFERENTIAL EXPANSION %
BOURRELET DETAIL 120 MM HOWITZER	4140 STEEL .805 WALL	40
BORE EVACUATOR 105MM HOWITZER (CONCENTRIC)	4130 STEEL 321 STAINLESS 7075 ALUMINUM .375 WALL (ALL)	66
BORE EVACUATOR 105 MM HOWITZER (ECCENTRIC)	4130 STEEL (.375) 4140 STEEL (.438)	40
BORE EVACUATOR 155 MM HOWITZER	304 ST. STEEL (.906) 347 ST. STEEL (.875)	125

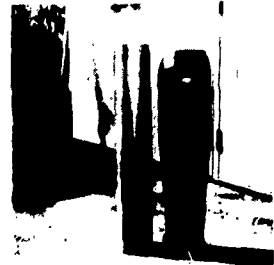


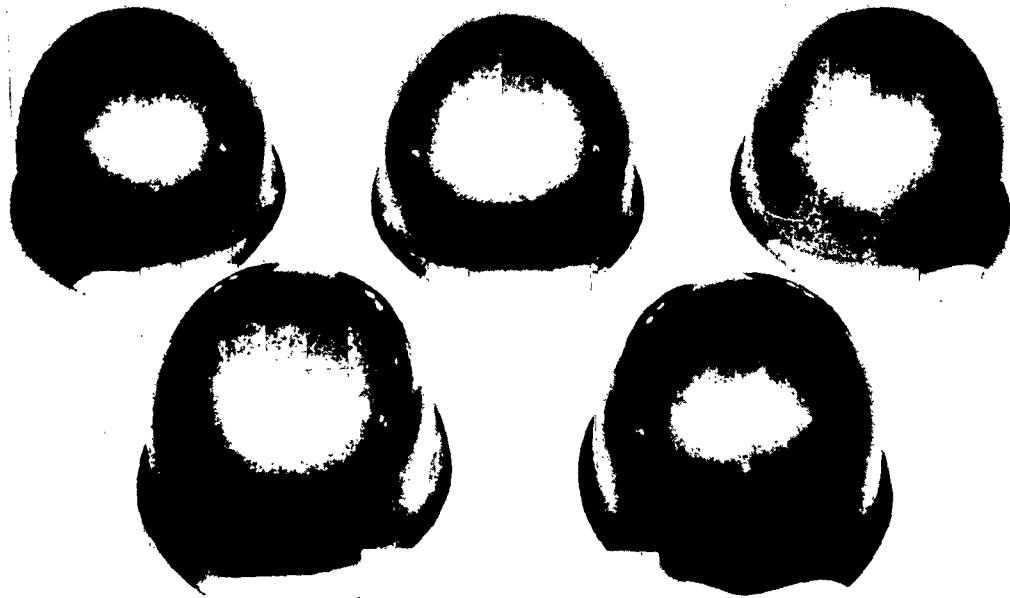
Figure 108. Courtesy of Grumman Aircraft Engineering Corporation

No production procurement has arisen from any of the above work as is pointed out in PEMA project submissions. The main obstacles are the need for low alloy material and the need for dies which will produce an appreciable quantity of these parts without die growth or breakage. It is felt, however, that the technology required to overcome these obstacles does exist in industry.

Figure 109 depicts explosively-formed 4Al 3Mn Titanium helmets. These helmets were formed at 1200°F by the use of alluvial sand. The contractor cited the following disadvantages for this method (45):

Extremely slow production rate.

Variation in thickness was considerably greater than desirable for maximum ballistic protection.



Group of completed helmets.
Covering is a vinyl protective coating.

Figure 109. Courtesy of Ryan Aeronautical Company

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Several other explosive forming users have stated that alternate methods may alleviate these difficulties. If this is true, an answer to the present heavy helmets may be at hand.

Other U. S. Army investigations include gun barrel lining, shock hardening of castings, 152mm bore evacuator forming, the blanking of machine gun barrel jackets, and the forming of baffle plates for muzzle brakes.

In summary, it would appear that there are U. S. Army applications for this method if the current technology can be fully utilized to overcome present problems. Further efforts should be directed toward the solution of these problems so that the monies invested can be effectively utilized.

(4) Other Explosive Metalworking: Explosives have been used to form screens without the degree of distortion normally associated with conventional methods. Shock hardening has been achieved on some materials which are not heat treatable. Plastics have been formed explosively (32). Some materials have been welded (bonded in a cold state) by the use of explosive forces. A few researchers have succeeded in cutting materials with explosives. A considerable amount of effort has been expended in the compaction of metal powder with explosives.

In summary, explosive methods have a definite place in both prototype and continuous production. It is hoped that the illustrations presented in this section will convey a definition of this "place" to the reader.

4. Conclusions: The main conclusions arising from this review and analysis are as follows:

a. Explosive metalworking techniques can be definitely applied to U. S. Army materiel.

b. Explosive forming has demonstrated a mobilization capability far beyond conventional methods as well as other new or nonconventional methods. This is particularly true when the part to be formed is large; such as, large armor sections.

c. The current level of activity indicates that the explosive forming method is a useful production technique.

d. The production capability of explosive forming remains to be developed to its fullest extent. Basic investigation of the forming parameters and economical mechanization is required to further develop its production capability.

e. Explosive forming application contract work should be performed by the firm which demonstrates the most successful experience in the application sought. This is due to the present empirical nature of the method.

f. Explosive forming is subject to limitations much the same as any other method. However, continuous progress is being made in reducing these limitations.

5. Recommendations:

a. The personnel of the U. S. Army Materiel Command should review present and future end item designs in light of the data presented in this publication.

b. The U. S. Air Force is presently considering contracts which will advance the conditions cited under Conclusion d. The personnel of the U. S. Army Materiel Command should follow the progress of this contract and incorporate any developments therefrom into future design and manufacturing technology programs.

c. Developments resulting from U. S. Army contracts should be widely disseminated so that maximum utilization of these developments (both favorable and unfavorable) can be achieved.

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* Recommended for those who desire further information.