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Superplastic Forming System Design

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1. Overview

The term superplasticity is used to describe the characteristic of certain metallic solids to attain large elongations, often exceeding 500%, under special conditions of controlled strain rate and temperature. Several aluminum, titanium, nickel, and ferrous alloys have been developed which exhibit superplastic behavior. The major use of superplastic forming (SPF) is in the aerospace industry where the advantages of light weight, high strength, and reduced fastener requirements make SPF particularly useful.

Compared to conventional sheet metal forming, SPF has greater design freedom, and offers the ability to produce lighter, more cost-effective components. For instance, the use of superplastic forming and diffusion bonding in the F-15E fighter jet fuselage resulted in a 15% weight savings and 44% cost savings over the conventionally fabricated structure. It also provided more room for equipment space in the fighter jet.[1]

1.1. Superplastic Phenomena

There are basically two modes of superplastic behavior: fine grained (or fine structure) and internal stress superplasticity. Most interest in SPF centers around fine grained superplasticity. SPF alloys in this mode have a strain-rate sensitivity of about .5 and deform principally by grain-boundary sliding.[2] The strain-rate sensitivity (m) is defined as follows:

$$m = \partial(\log \sigma)/\partial(\log \dot{\varepsilon})$$

where σ = stress

$\dot{\varepsilon}$ = strain rate

Superplastic metals demonstrate maximum elongations when the strain rate sensitivity reaches its maximum value. The strain rate sensitivity is affected by the strain rate, temperature, and grain microstructure. At very low strain rates, superplastic alloys exhibit strain rate sensitivities that are essentially equal to the coarse grained material. However, at intermediate strain rates, a transition occurs in superplastic metals which leads to a high strain rate sensitivity, enabling large elongations.[3]

1.2. Characteristics of Selected Superplastic Metals

The superplastic alloys receiving the most attention are aluminum-lithium alloys, low alloy aluminum, titanium, and Inconel 718. These are discussed briefly in the following sections.

1.2.1 Al-Li Alloys

Aluminum-Lithium superplastic alloys are currently attracting much attention for aircraft and aerospace uses. This is due to the fact that Li is one of only two alloying agents that increases the elastic modulus in aluminum while simultaneously decreasing its density.[4] Significant weight savings can be realized by using Al-Li alloys in flight hardware; this benefit can be further utilized by using SPF to manufacture suitable components.

Two groups of Al-Li alloys have been developed with superplastic behavior. The first group contains high levels of zirconium (0.5 wt%). The second group has low Zr levels; alloys in this group are manufactured by ingot metallurgy and powder metallurgy. As with all aluminum alloys, Al-Li alloys must undergo thermomechanical processing to attain superplasticity. Before this processing, these alloys have strain rate sensitivities of about .25, and ductilities of 100-200%; after processing, the strain rate sensitivities jump to about .4, and ductilities of between 500%-1000%.[3]

The optimum superplastic behavior in Al-Li alloys occurs at strain rates of 20-50%/min which is much greater that many other aluminum alloys. For instance, Al 7475 has optimum superplastic behavior at about 1-2%/min. The high strain rates obtained in the Al-Li alloys are clearly advantageous for superplastic forming. Some of the Al-Li alloys that are being used in SPF operations are 2090, 2091, 8090. The lithium level typically ranges between 2 and 3% by weight. Copper is sometimes added to control the size and distribution of the Al_3Zr phase, which affects the superplastic deforming behavior.[3]

One problem with SPF of aluminum is cavitation. At elongations of 150% or more, internal voids, known as cavitation, form which have a very detrimental effect on the material properties of aluminum. Specifically, the tensile strength and ductility are greatly reduced. Imposing a hydrostatic back pressure is the most effective way to combat cavitation. Cavitation is almost completely suppressed by using back pressures greater than 2 or 3Mpa (290-435psi).[5] Cavitation can also be reduced by annealing the material before and after superplastic straining. This process gives the alloy greater homogeneity and sinters small cavities formed during thermo-mechanical processing. Annealing before strain, however, reduces the superplastic behavior of the material by inducing grain coarsening.[4]

1.2.2 Other Superplastic Aluminum Alloys

The Supral family (100, 150, 200, 220), several 2000 series, some 5000 series, and some 7000 series aluminum alloys have been processed to obtain superplasticity. These alloys have found markets in the public transport, electronics, architecture, automotive, and aircraft/aerospace industries. Their attractiveness comes from their ability to form complex shapes with complex curvature, steps, angles, and styling features from sheet metal in a single process step.[6]

These alloys require extensive thermo-mechanical treatments to become superplastic. However, tooling is inexpensive, significant weight reductions can be achieved, and enhanced structural integrity can be imparted using SPF.

Most aluminum SPF is done at between 370 and 550°C. Forming pressures are very low, ranging from 15 to 80 psi. Back pressures of 250-300 psi are typically used to prevent cavitation.

The aluminum alloy 2004, known as Supral 100, is superplastic over quite a large range, 360-500°C. At the lower end of this range, it exhibits elongations of about 300%; the maximum elongation attainable approaches 1300% and occurs at about 450°C.

Thermo-mechanically processed Al7475 has been used quite extensively in the aircraft industry due to its high strength, low density, and heat resistance. As mentioned earlier, the major drawback in superplastic forming of this alloy is its long cycle times due to the very low strain rates (1-2%/min) that must be used to produce high elongations.

1.2.3 Superplastic Titanium Alloys

The alpha-beta titanium alloys, including Ti-6Al-4V and Ti-6Al-14V, are unusual in that the standard mill-run sheet can be superplastically formed. They can also reach elongations of up to 2000% under the optimum SPF parameters.[7] These facts coupled with titanium's high strength and heat resistance make titanium SPF very useful in the aircraft/aerospace industry. Superplastic Ti alloys are generally formed at 850-950°C (1562-1742°F). They can be formed at slightly lower temperatures if the strain rate is reduced. No back pressure is needed in the superplastic forming of Ti alloys, because cavitation is usually not a problem with SPF Ti.

Forming pressures vary between 80 and 200 psi, depending upon the size and thickness of the sheet to be formed, the degree of detail required in the finished part, and the forming temperature. Forming cycles of 2-3 hours or more are common.

1.2.4 Superplastic Nickel Alloys

Inconel 718 and IN 100 are two nickel based superalloys which have been processed for superplastic forming. These alloys are being used for turbine blades and other aircraft components which will encounter high temperature service. Inconel 718SPF has been developed by Inco Alloys for superplastic forming. It has a grain size of ASTM 10, or smaller. To form Inconel 718, 2mm sheets are placed between two ceramic platens at temperatures of between 950 and 1100°C and subjected to argon gas pressure at 300 psi for up to four hours. The properties of the formed part can be further improved by a standard solution anneal plus aging treatments. [8] Cavitation is a factor with SPF of Inconel 718; it is affected by the strain rate and back pressure. The development of cavities is insignificant at a strain rate of 10^{-2} s^{-1}, but becomes more dominant at decreasing strain rates. In effect, the tensile properties of Inconel 718 are retained through engineering strains through 200%.[9]

1.3 Design Aspects of SPF Parts

A superplastic forming process is usually motivated by some or all of the following design factors:

1. complex curvature of the candidate part
2. desire to reduce the number of required parts and fasteners
3. relatively low production numbers
4. desire to reduce weight
5. possibility of using diffusion bonding in conjunction with SPF to form internal stiffeners
6. reduced tooling costs

1.3.1 Designing for Superplastic Forming

Superplastic forming is basically a stretching operation, and as such, causes the material to thin-out as it is formed. The average thinning is proportional to the increase in surface area. Local thinning is affected by details in the tool such as radii, ribs, raised bosses, draft angles, ridges, and valleys.

There are three main forming techniques which have been developed for forming single layer shapes. They include male forming, female forming, and drape forming. These techniques are illustrated in Fig. 2-4. Male forming allows the greatest control of metal flow and allows deeper, more complex shapes to be formed than the other two methods. One disadvantage in male forming is that there must be a moving male die inside the toolbox; obviously, this adds to the complexity of the process.

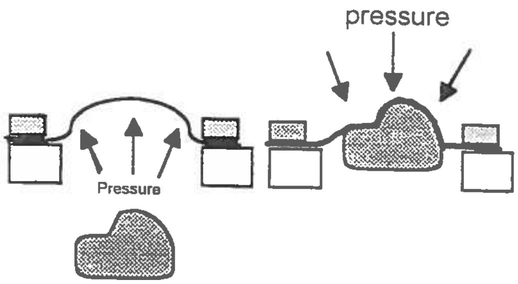


Figure 2 - Male Forming

The heated sheet is blown into a bubble. The tool is then pushed up into the bubble and the sheet is blown back over the tool.

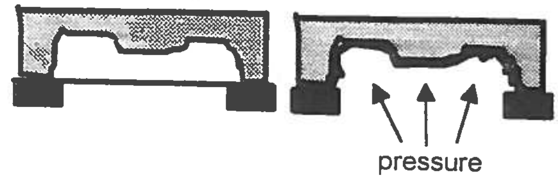
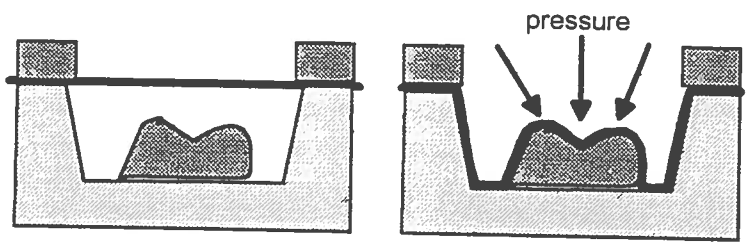


Figure 3 - Female Forming

The sheet is blown into the female mold and assumes the shape of the tool cavity.

The heated sheet is draped over the male tool.

Fig. 4 - Drape Forming

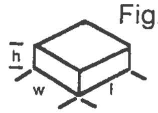


Female forming is very simple, however, the tool must be strong enough to withstand the forming pressures which may be upwards of 150psi. Expensive steel tools are often required for this type of forming.

Drape forming is convenient in that a "generic" toolbox can be developed which can withstand the forming pressures. Different parts can be formed simply by placing a different tool in the toolbox. This tool can be made of an inexpensive ceramic rather than steel.

The most important factor when considering a design for superplastic forming is the aspect ratio.[10] The aspect ratio defines the relationship between the plan dimensions and the height, as shown in Fig. 5.

Fig. 5 - Aspect Ratio



aspect ratio = 2*h/(w+l)

The maximum allowable aspect ratio used in a design depends upon the type of forming (male, female, or drape), the dimensions of the part, and the local detail desired, such as small corner radius. If the detail is very high, a lower aspect ratio is needed. Also, if L increases above 2*W, the aspect ratio may have to be reduced. If generous radii are used, a larger aspect ratio may be attainable. Ranges for aspect ratios depending upon the type of forming are listed below.

Forming Type	Aspect Ratio
Male	.45-.5
Female	.3-.35
Drape	.2-.25

(Table extracted from "Designing for Superplastic Forming")

There are also limits on typical features that are commonly encountered in SPF operations. Some examples are shown in Fig. 6.[11]

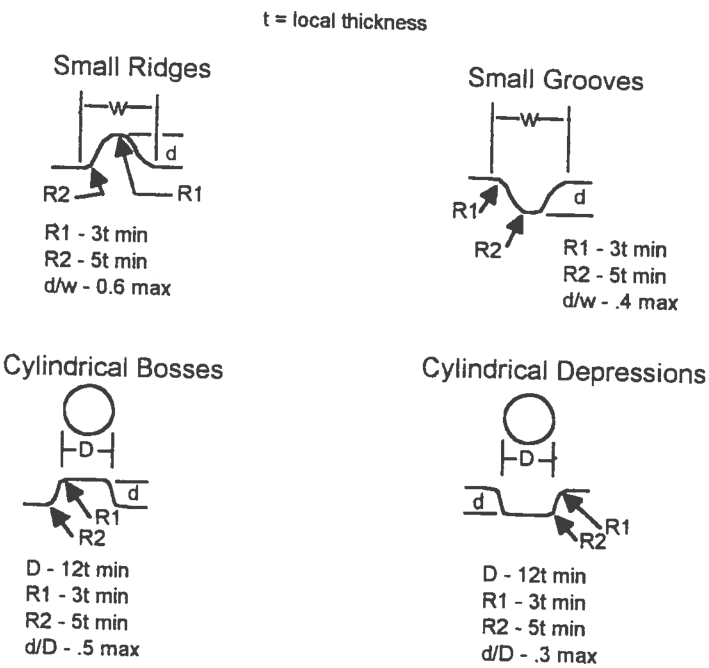


Fig. 6 - Typical Feature Limitations
(Extracted from "Designing for Superplastic Forming")

There are also limitations on the minimum radii on the periphery of the tool. The forming process will not allow sharp corners. The minimum values for the section radius, flange radius, and plan radius are shown in Table 2. Radii nomenclature are shown in Fig. 7.

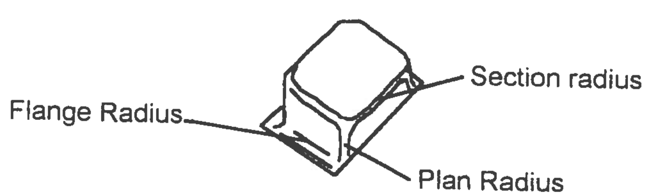


Figure 7 - Radii Nomenclature

	Aspect Ratio	Plan Radius	Section Radius	Flange Radius
Male and Drape	.4-.5	15T	7T	4T
	.3-.4	12T	6T	5T
	.2-.3	10T	5T	5T
	.1-.2	7.5T	4T	6T
	.0-.1	5T	3T	6T
Female	.2-.35	13T	10T	5T
	.1-.2	9T	7T	4T
	.0-.1	7T	5T	3T

Table 2 - Recommended Minimum Radii
(Extracted from "Designing for Superplastic Forming")

The sheet thickness decreases as the forming progresses. The average final thickness of the sheet is related to the ratio of the surface area of the completed part to the initial area of the sheet.[12]

$AverageFinalThickness = TF * T * PA/A$

T - Starting Thickness

PA - Plan area of component

A - Total surface area of component

TF - Thinning factor (depends upon forming technique, Male TF - 1.2, Female TF - 1.0, Drape TF - 1.1)

2. Design of Experimental SPF Process

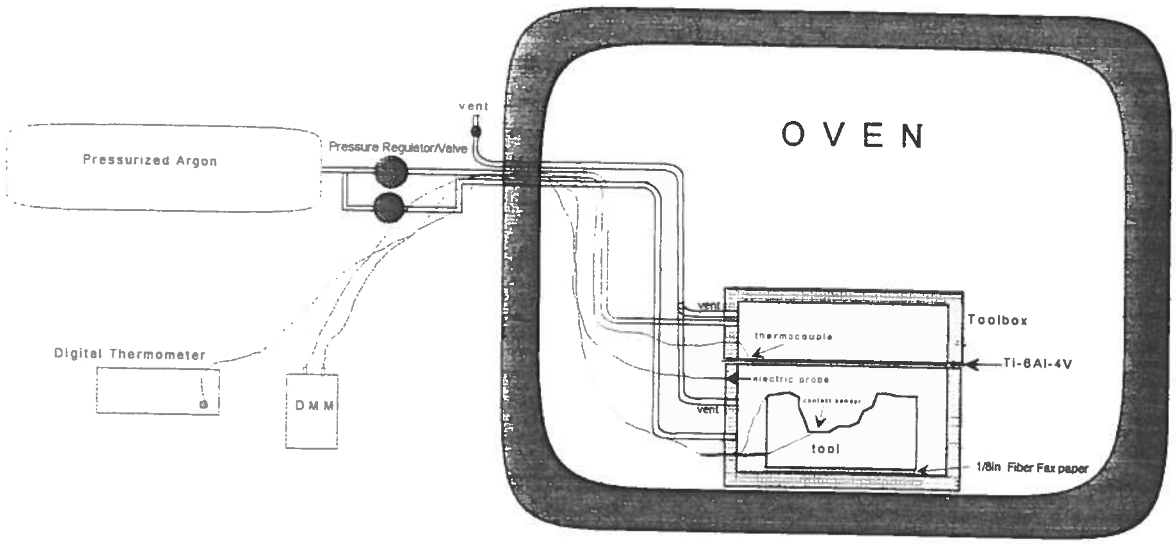
In order to begin SPF research and manufacturing at Marshall Space Flight Center (MSFC), an experimental design was developed which would allow testing of Ti alloys, specifically Ti-6Al-4V, and eventually Al and nickel alloys. The design was directed and in some cases limited by available resources at MSFC .

The basic setup consists of a toolbox which contains a sheet of superplastic alloy, an oven, and a gas feed and management system. The system configuration is shown in Fig. 8. This system will allow the forming of Ti-6Al-4V and aluminum alloys, but will require some additional equipment to form Inconel 718SPF. Details of the toolbox, gas management system, and the oven are given in following sections.

The process steps are listed below:

1. Place a thin layer, 1/8in., of Fiber Fax paper on the bottom surface of the toolbox. (This prevents stress concentration in the ceramic tool.)
2. Place the ceramic tool in the toolbox on the Fiber Fax paper.
3. Connect the contact sensors and thermocouples in the tool to the lead wires in the toolbox.

Figure 8 - SPF System



4. Rub the parting agent, boron nitride, on the mating surfaces of the toolbox and the blank.
5. Place the sheet to be formed on the toolbox base. Use the guide holes to line it up.
6. Place the thermocouples in contact with the sheet using a ceramic putty to bind them.
7. Clamp the lid and base of the toolbox together with the sheet between them.
8. Place the toolbox in the oven and begin heating.
9. Run the gas feed lines, the thermocouple leads, and the sensor leads through the feed through hole in the side of the oven.
10. Seal the feed through hole with ceramic putty.
11. Connect the pressure lines to the high pressure argon source. Connect fittings for ventilation to the vent lines.
12. Begin pumping argon through the toolbox to flush the air from the toolbox.
13. Connect the thermocouples to the digital thermometer.
14. Connect the contact sensors to the digital multi-meter and set for continuity check.
15. When all the thermocouples reach a steady state reading of 1600°F (target temperature is 1600°F, ±50°F), steadily increase the forming pressure in the toolbox to 80 psi. The forming pressure can be varied; the higher the forming pressure, the less elongation that can be achieved.
16. The pressure, temperature, and contact sensors should be monitored closely.
    - If the pressure changes abruptly, the sheet has probably ruptured and the forming pressure should be dropped.
    - When continuity between all sensors has been achieved, the part is fully formed, and the forming pressure can be removed.

17. The sheet should be brought back to ambient temperatures as quickly as possible. This may be accelerated by circulating argon through the toolbox.
18. When the toolbox is sufficiently cool, it may be removed from the oven.
19. The sheet should be evaluated for surface defects, localized thinning, strength, and cavitation.

This process should be repeated using a number of different forming temperatures and pressures to determine the optimum parameters.

2.1 Toolbox Design

The toolbox is the structural pressure vessel which contains the tool and superplastic sheet during forming. It must be designed to maintain a tight seal around the mating edge of the toolbox and the sheet. High pressures along with elevated temperatures dictate that the toolbox must be made of a superalloy or refractory metal. Inconel 718 was chosen for the toolbox design because of its availability at MSFC and its high temperature strength. The temperature limit for Inconel 718 in structural applications is about 950°C. This is right at the upper limit for titanium superplastic forming.

The toolbox is a rectangular box, 16in. by 14in. by 7in., with a 1in. overhang on all sides for bolting purposes. See Appendix A for illustrations and stress analysis. The box is composed of two sections - the lid and base. All sides of the box are constructed of 1in. Inconel 718 plates. Each of the two sections have an inlet and a vent hole for purging the chamber with Argon and then applying the forming pressure. The base also has a small tapered hole drilled in one side to allow thermocouples and contact sensors to be run through. This hole will be patched with ceramic putty to seal the box during forming. Along the mating surfaces of the lid and base, a step cut has been machined into the edges to provide a bite into the superplastic sheet and seal the chamber. The cavity dimensions of the base are 14in. by 12in. by 4in. The allowable size of the toolbox is severely limited by the forming pressures and the elevated temperatures encountered during superplastic forming. Eight 3/8"dia. molybdenum bolts will be used to clamp the toolbox closed during forming. The stress analysis for these bolts is also provided in Appendix A.

2.2 Gas Flow System

The gas flow system consists of a high pressure Argon tank, two pressure regulators, four manually controlled valves, four runs of stainless steel tubing, and the required fittings. The Argon will be used to purge the chamber before forming begins. Argon will be pumped through the inlets in the toolbox and out through the vent holes and outlet tubing. After about 15 minutes, all valves will be closed. The toolbox and sheet will be brought up to forming temperature. Argon will be pumped through the system at a slow flow rate to insure an inert environment. Once the toolbox reaches the target temperature, the pressure in the lid will be brought up gradually to begin forming. The pressure will be monitored closely and adjusted accordingly to follow the prescribed pressure - time curve for that run. After contact has been made between the sheet and the deepest section of the tool, if failure hasn't occurred, the pressure will be reduced and Argon will be pumped through the toolbox vent holes for about 15 minutes to accelerate the cooling cycle and to prevent oxidation of the toolbox and formed sheet.

2.3 Oven

The ABAR oven in building 4767 will be used in this project. It can maintain a temperature of 2000°F, and has feed-throughs for all tubing and monitoring instruments. It also can provide an inert environment to prevent oxidation of the Inconel 718 box.

3.0 Recommendations

For testing purposes, a conical or dome shaped die may be used to determine the optimum temperature and pressure curve for each alloy tested. A SPF sheet can be tested to rupture, and the elongation can be readily determined by the depth of forming in the tool. For a specific part, the optimum temperatures and pressure vs. time curves must be determined by experimentation and experience. This process may be benefited by the use of nonlinear finite-element codes such as MARC which have been developed for superplastic forming applications.[13] The pressure curve depends upon the depth of forming, the temperature, and the degree of detail in the finished part.

The Tugucci method may offer a good approach to determine the relationship between independent and dependent variables in the process. As mentioned above, the independent variables include forming temperature, forming schedules (what pressure should be applied at any given time), the initial starting thickness, the forming technique (male, female, or drape), and the material to be formed. The dependent variables include final thickness (will vary from point to point), final tensile properties, degree of cavitation, surface finish, etc.

It may be possible to experiment with diffusion bonding in the proposed SPF system. Diffusion bonding is often easily incorporated into the SPF process. This bonding technique has been used to manufacture hollow turbine blades, ribbed structural reinforcements, and various other layered components. Due to the difficulty in preventing oxide layer formation in aluminum alloy during SPF, solid state diffusion bonding of aluminum alloys is not attempted often.[14] However, titanium diffusion bonding is relatively easy and is very popular for manufacturing integrally stiffened structures.

Another promising area of interest is the Vacuum Plasma Spray lab run by Rocketdyne Industries in MSFC bldg. 4707. Vacuum plasma sprayed material may be processed with a high density and superfine grain structure. It may be possible to produce aluminum alloys with superplasticity using this method. Lee Flanigan or Bill Davis, both of Rocketdyne, may offer some assistance in investigating this matter.

4.0 Conclusion

Superplastic forming offers the ability to fabricate components with complex curvature and fine detail from sheet metal in a single step. Significant weight savings can be achieved, while also reducing the number of fasteners required. When used with diffusion bonding, SPF/DB provides the ability to manufacture structural members with integral reinforcements.

The system outlined in this report is designed to facilitate Ti-6Al-4V and various aluminum alloys to be evaluated at various temperatures and pressures. It also offers the flexibility of using ceramic tools which are much less costly than steel tools. By casting several tools with differing aspect ratios and detail, general guidelines can be determined for estimating the appropriate forming cycles for different types of parts. The system is not suitable for Inconel 718SPF processing; however, the principle remains the same. To use this system, the interior of the toolbox must be insulated with Nexel 900 or an equivalent insulation. Ceramic heating platens can then be placed inside the toolbox and used to bring the interior of the chamber to forming temperature. A heat transfer analysis of the system should be done to insure that the toolbox does not reach temperatures which would reduce its strength to dangerous levels.

[1] E. J. Tuegel, Pruit, and Hefti. "SPF/DB Takes Off." Advanced Materials and Processes July 1989: 36-41.

[2] O. D. Sherby and J. Wadsworth. "Superplasticity and superforming processes". Materials Science and Technology, Nov. 1985. Vol. 1 Number 11; pg 924-935.

[3] W. D. Nix. "On Some Fundamental Aspects of Superplastic Flow." Superplastic Forming. Ed. Suphal P. Agrawal. Metals Park, Ohio: American Society for Metals, 1985. 3-12

[4] Jeffrey Wadsworth. "The Development of Superplasticity in Aluminum-Lithium Based Alloys." Superplastic Forming. Ed. Suphal P. Agrawal. Metals Park, Ohio: American Society for Metals, 1985. 43-57

[5] A. Varloteaux, Blandin, and Suery. "Control of Cavitation During Superplastic Forming of High Strength Aluminum Alloys. " Materials Science and Technology Nov. 1989: 1110-1117.

[6] R. J. Stracey. "New Market Promise for SPF Aluminum." Mctallurgia Nov. 1992: 412.

[7] William R. East. "Superplastic Forming for Tomorrow's Metal Manufacturing." Materials Engineering Apr. 1988: 37-40.

[8] "Superplastic Forming Sheet Alloy Developed." Metallurgia Nov. 1992: 406.

[9] Gaylord D. Smith and Daniel H. Yates. "Superplastic Forming of Inconel Alloy 718SPF." Huntington, WV, Inco Alloys International, Inc.

[10] "Designing for Superplastic Forming." (A design guide for components to be superplastically formed from sheet aluminum alloys.) Riverside, California: Superform USA, Inc., Issue No. 1, Oct. 1990.

[11] "Designing for Superplastic Forming" (A design guide for components to be superplastically formed from sheet aluminum alloys.) Riverside, California: Superform USA, Inc., Issue No. 1, Oct. 1990.

[12] "Designing for Superplastic Forming" (A design guide for components to be superplastically formed from sheet aluminum alloys.) Riverside, California: Superform USA, Inc., Issue No. 1, Oct. 1990.

[13] E. J. Tuegel, Pruit, and Hefti. "SPF/DB Takes Off." Advanced Materials and Processes July 1989: 36-41.11

[14] E. J. Tuegel, Pruit, and Hefti. "SPF/DB Takes Off." Advanced Materials and Processes July 1989: 36-41.

APPENDIX A

Toolbox Design

Toolbox Analysis

The toolbox is fabricated from 1in. Inconel 718 plates, overaged and solution treated. The area exposed to the pressure is 14in. by 12in. The box is exposed to a maximum pressure of 200psi (1.38Mpa) at 1600F (870C); and 500psi (3.45Mpa) at 1022F (550C).

The toolbox lid must bear the greatest load due to the surface area affected by the pressure.

The equations for stress in a plate supported on all edges and exposed to a uniformly distributed load are as follows:

$a := 13.5 \cdot in \qquad b := 11.5 \cdot in \qquad w := 200 \cdot psi \qquad t := 1 \cdot in$

$$\sigma := \frac{1}{2} \cdot \left(\frac{a^2}{b^2 + a^2} \right) \cdot w \cdot \frac{b^2}{t^2}$$

$$\sigma = 7.664 \cdot 10^3 \cdot psi$$

For the sides:

$as := 13.5 \cdot in \qquad bs := 5 \cdot in \qquad w := 200 \cdot psi \qquad ts := 1 \cdot in$

$$\sigma s := \frac{1}{2} \cdot \left(\frac{as^2}{bs^2 + as^2} \right) \cdot w \cdot \frac{bs^2}{ts^2} \qquad \sigma s = 2.198 \cdot 10^3 \cdot psi$$

The force acting on the lid is as follows:

$$F := w \cdot a \cdot b \qquad F = 3.105 \cdot 10^4 \cdot lbf$$

The weld stress is given below:

$tw := 2 \cdot .707 \cdot .125 \cdot in \qquad A := tw \cdot (2 \cdot a + 2 \cdot b)$

$$\tau := \frac{F}{A} \qquad \tau = 3.513 \cdot 10^3 \cdot psi$$

$Sy := 48000 \cdot psi$ (Inconel 718 at 1600F.)

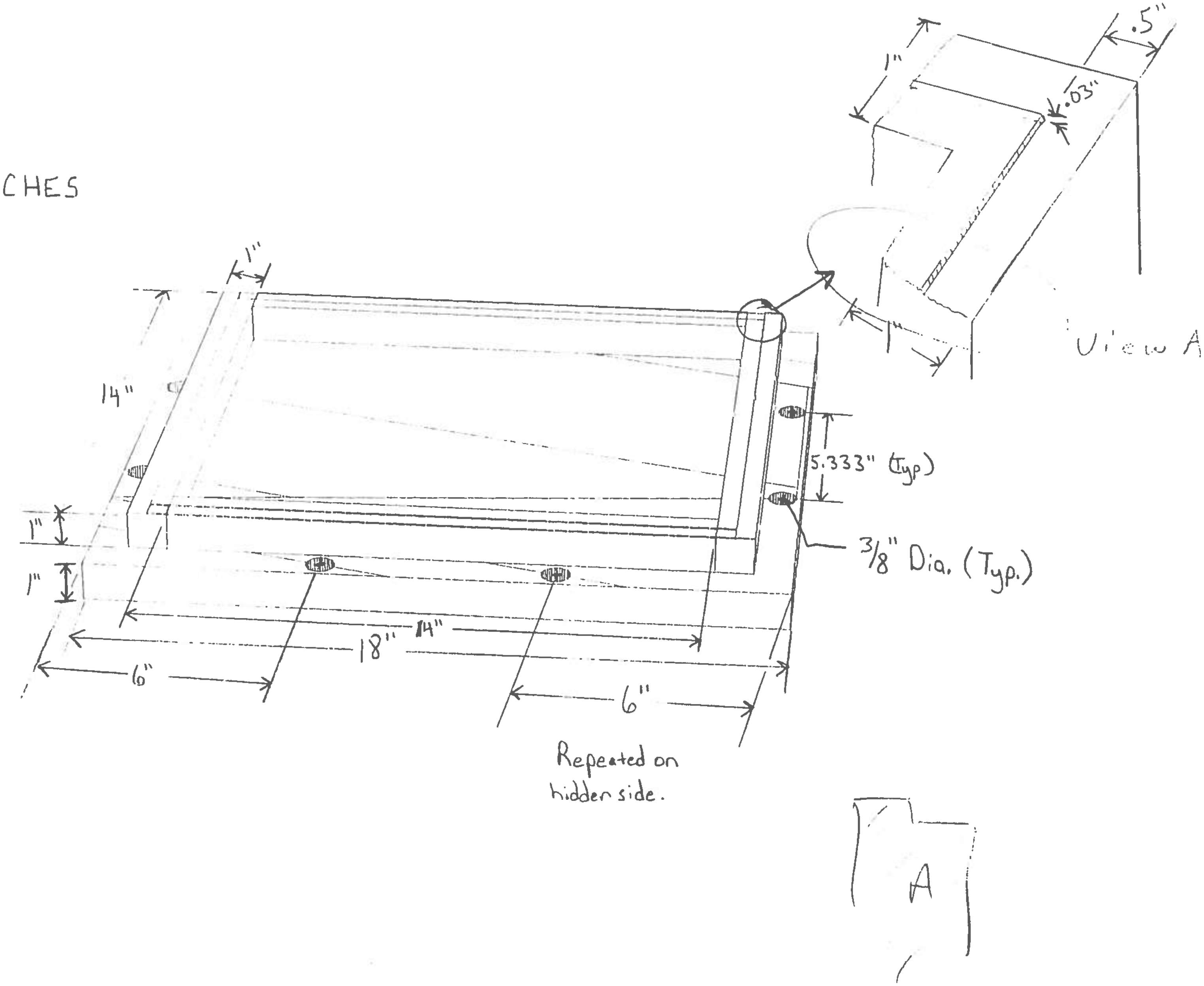
$Ssy := .58 \cdot Sy$

$$SF := \frac{Ssy}{\tau} \qquad SF = 7.924$$

This is well within the safe limit for Inconel 718.

NTS

All DIMENSIONS ARE IN INCHES



DETAIL: TOOLBOX LID

For 500psi at 1022F.

Lid Analysis

$w := 500 \cdot psi$ $Sy := 137000 \cdot psi$ (Inconel 718 at 1000F.)

$\sigma := \frac{1}{2} \cdot \left(\frac{a^2}{b^2 + a^2} \right) \cdot w \cdot \frac{b^2}{t^2}$ $\sigma = 1.916 \cdot 10^4 \cdot psi$

$SF := \frac{Sy}{\sigma}$ $SF = 7.151$

Side Analysis

$\sigma s := \frac{1}{2} \cdot \left(\frac{as^2}{bs^2 + as^2} \right) \cdot w \cdot \frac{bs^2}{ts^2}$ $\sigma s = 5.496 \cdot 10^3 \cdot psi$

$SF := \frac{Sy}{\sigma s}$ $SF = 24.927$

The force acting on the lid is as follows:

$F := w \cdot a \cdot b$ $F = 7.762 \cdot 10^4 \cdot lbf$

The weld stress is given below:

$tw := 2 \cdot .707 \cdot .125 \cdot in$ $A := tw \cdot (2 \cdot a + 2 \cdot b)$

$\tau := \frac{F}{A}$ $\tau = 8.784 \cdot 10^3 \cdot psi$

$Sy := 137000 \cdot psi$ (Inconel 718 at 1000F.)

$Ssy := .58 \cdot Sy$

$SF := \frac{Ssy}{\tau}$ $SF = 9.046$

Bolt Analysis

3/8" - 16 Molybdenum bolts will be used to clamp the toolbox closed during the forming operation. Two bolts will be used on each side.

Total force acting on lid:

$w := 100 \cdot psi$

$F := w \cdot a \cdot b$

$F = 1.552 \cdot 10^{4} \cdot lbf$

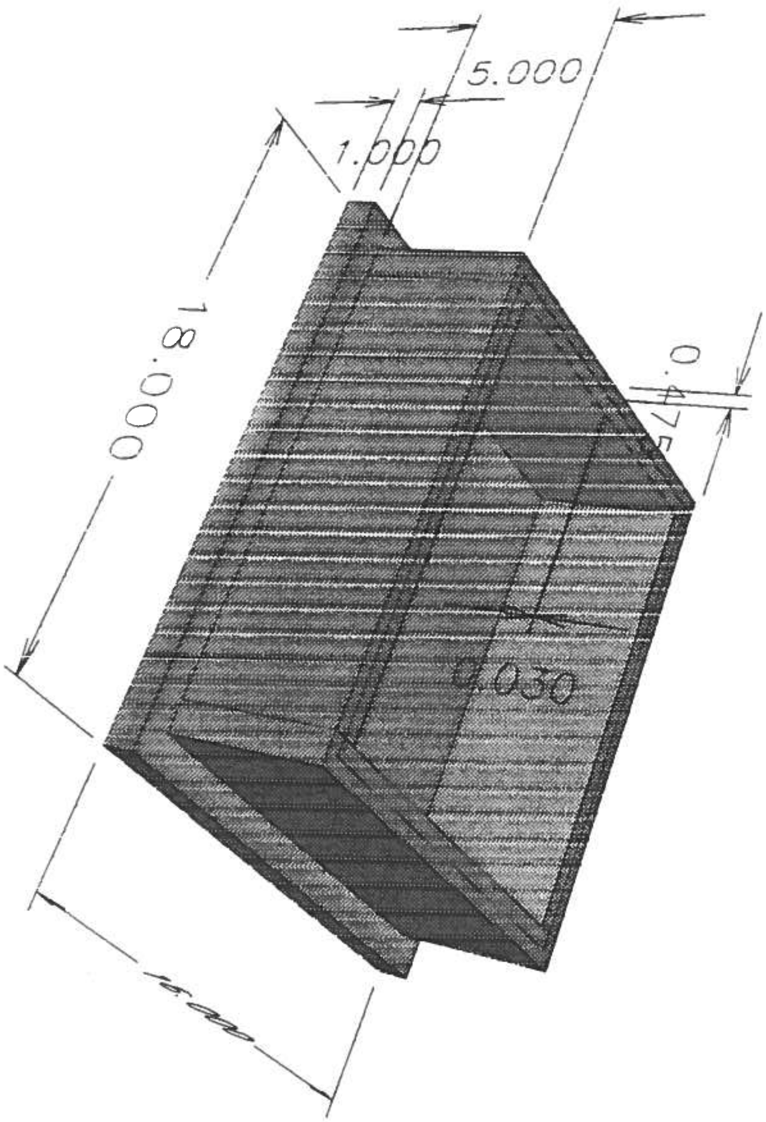
Force that each bolt can carry:

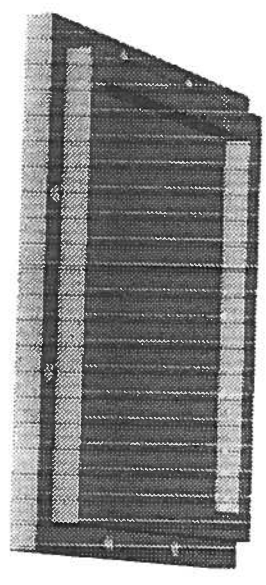
$At := .0775 \cdot in^{2}$ $\quad Sy := 60000 \cdot psi$

$Fb := At \cdot Sy$ $\quad Fb = 4.65 \cdot 10^{3} \cdot lbf$

$Number\_of\_bolts\_required := \frac{F}{Fb}$ $\quad Number\_of\_bolts\_required = 3.339$

Eight bolts are available to us at this time; to insure a safety factor of two, the pressure inside the chamber must be limited to 100psi.


5.000
1.000
18.000
0.475
0.030



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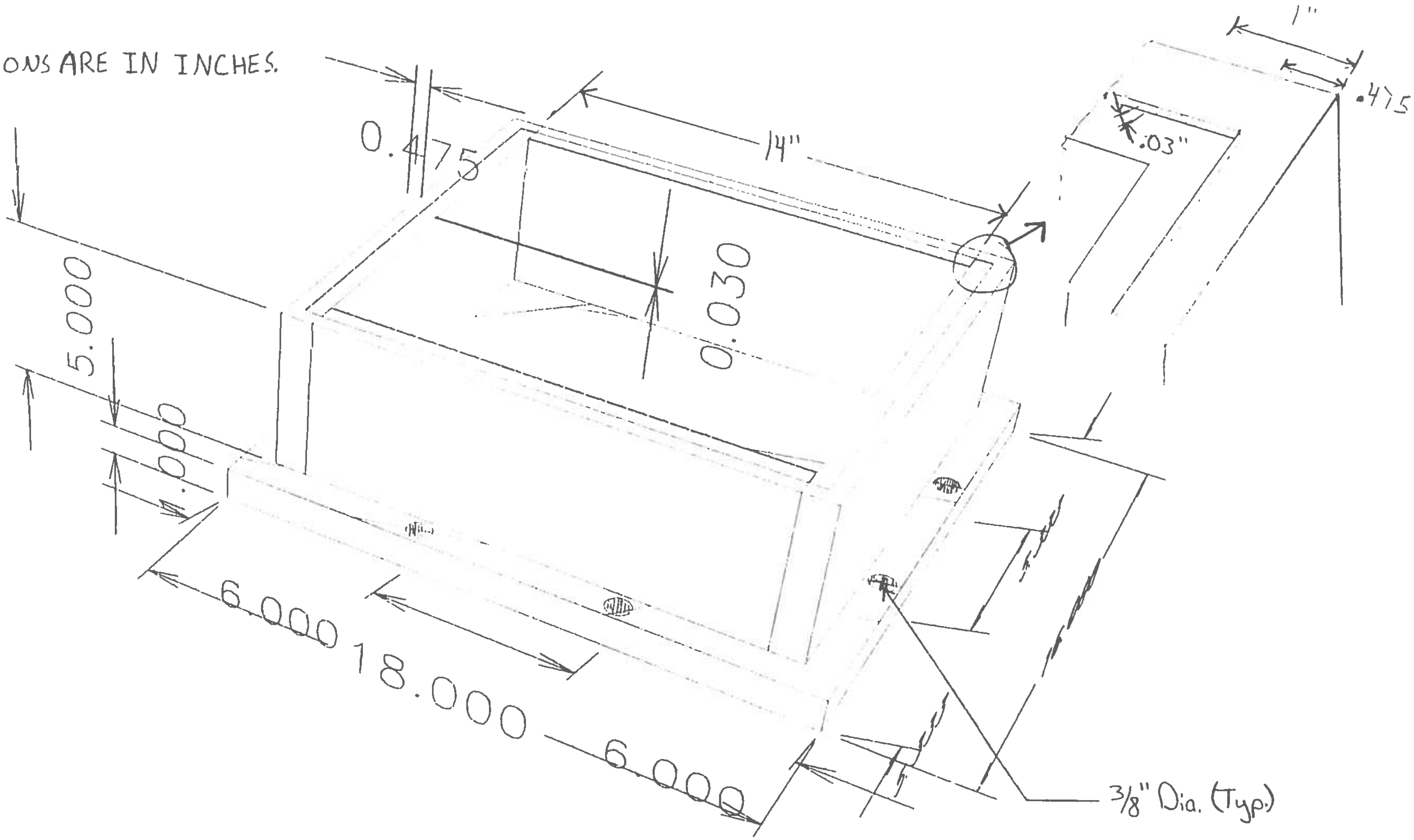
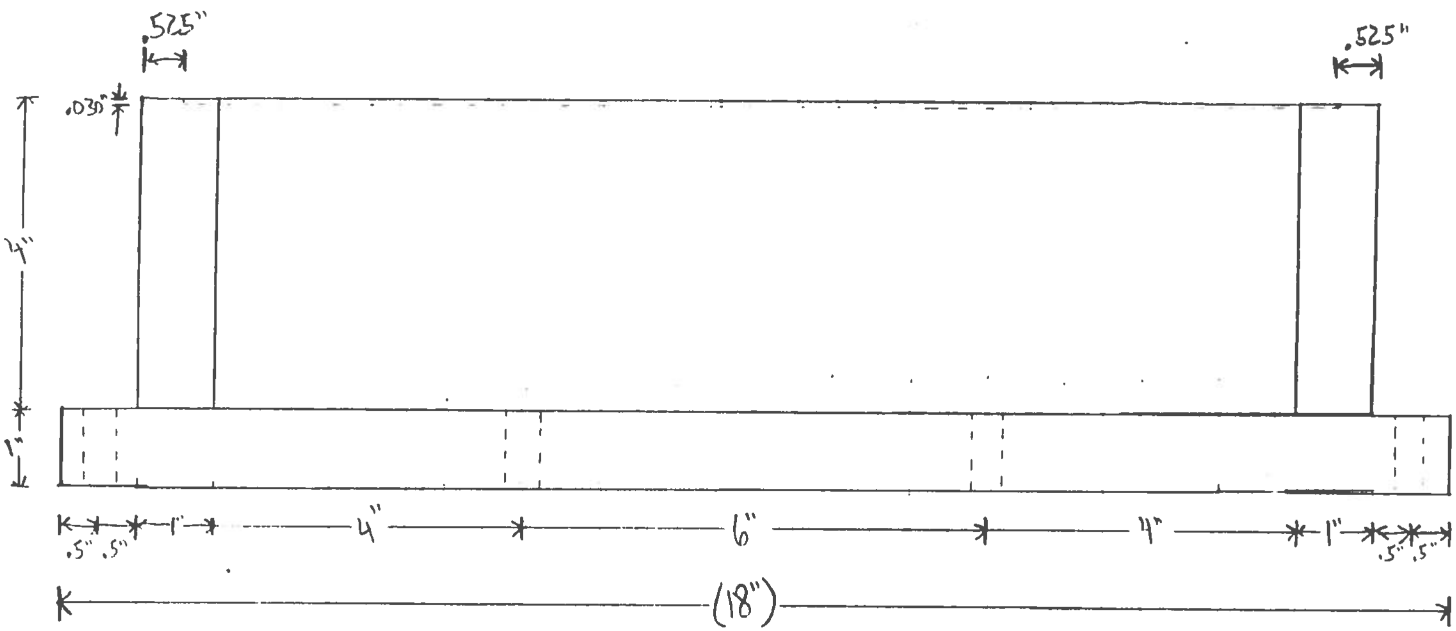
All DIMENSIONS ARE IN INCHES.



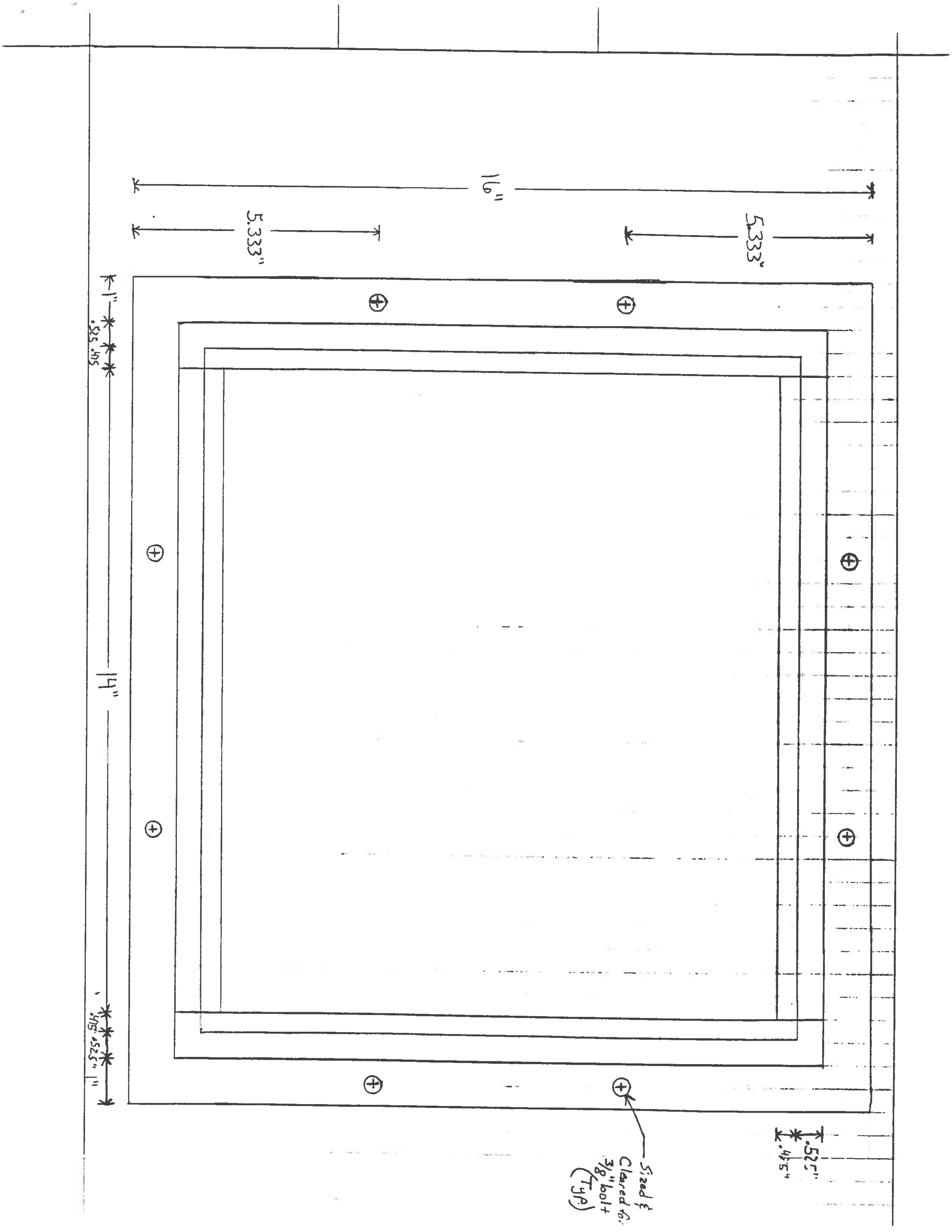
DETAIL: TOOLBOX B...

SPF Toolbox

Front View



Material: 1" plate Inconel



16"
5.333"
5.333"
1"
.525
.475
14"
.475
.525"
1"
.525"
.475"
Sized & Cleared for 3/8" bolt (Typ.)