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STRUCTURAL ANALYSIS OF TURBO-GENERATOR IN ELECTRONIC FUZE

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ABSTRACT

Traditionally storage batteries were used as a power source for fuzes. To overcome their shortcomings like short life, chemical leakages, unreliability etc; a new technology was required. R&D was carried out, which resulted in the development of wind driven turbo generator that could fit inside the fuze ogive. The obvious advantages of such a power source were long life, nonhazardous storage & greater reliability. So, it has become the most preferred choice for use in artillery munitions etc. Turbine and shaft-magnet assembly are the most critical components of the turbo generator. So the accurate designing and analysis of the turbo generator is needed, because failure will lead to high losses. So high priority is given to its testing and analysis.During flight, the projectile experiences varied climatic conditions which changes the stress induced in the rotor that have been successfully analysed. The meshing and static structural analysis is carried out in ANSYS WORKBENCH 14.5 software.

KEYWORDS: Turbo-Generator Air Intake Valve Power Sources Design & Analysis Rotor Shaft

INTRODUCTION

The power supply unit is a very critical component of a fuze. It fulfills the power requirements of the electronic circuit, which controls the warhead detonation.

The various power sources that have been used are [1]: --

- *Piezoelectric power supply,*
- *Thermal battery,*
- *Reserve battery.*

Among these the use of reserve battery has been more prominent.

A brief description of the above mentioned power sources are given below:

Piezoelectric Power Supply

The piezoelectric element has been placed in the nose of the fuze ogive to produce electrical energy upon impact of the warhead. This produced energy is allowed to pass through a detonator which is a thin wire surrounded by a sensitive explosive, such as lead azide. Explosion of the lead azide causes the main explosive charge in the warhead to detonate.

Drawback: Piezoelectric elements located in the nose offer only a limited area of impact, and the voltage output is a function of the impact angle, falling off as the angle increases.

Thermal Battery

Setback forces, which are generated when the round is fired, produce the electric energy. A fuzed salt is released on setback, which subsequently causes an electrical charge to be generated between two electrodes. This charge is stored in a capacitor and used to set off the detonator upon collision of the warhead.

Drawback: Requires a considerable volume of space, necessitating minimization of the amount of explosive. For a given warhead size, it also increases the weight of warhead.

Reserve Battery

They have been primarily lead/lead dioxide/fluboric acid based batteries. Further they may be either dry cell based or wet cell based. Dry cell batteries have limited useful lives. Wet cell batteries are used such that the electrolytic fluid is injected automatically into the electrodes, as a result of shell spin after leaving the gun. Batteries may not be stored separately from the electrical portion of the fuse, which they are to power, but must be preassembled with the fuzes, for logistic reasons.

Drawback: Some types of battery-equipped fuzes have proven to be unreliable, as a result of electrolyte fluid leakage. They have a low shelf life (5-10 years). Another problem is that these batteries are difficult to manufacture so that at the onset of a national emergency production levels are expected to lag requirements for several months, thereby creating logistics problems. Also they are expensive.

To overcome the drawbacks of the previously employed power supply sources, so as to avoid logistics problems in case of a national emergency, new avenues in the case of power supply source have been sought. Some of these are: -

Thermoelectric Power Supply

Turbo-Generator

Thermoelectric Power Supply

It comprises of a plurality of junctions, which are coupled to the propellant for sensing the temperature which serves a means of generating a voltage in response to the temperature sensed by the generator. It works on the thermocouple effect. Integrated with a compatible impact sensor (triboluminescent) it will initiate the warhead’s explosive warhead. The voltage generated by the thermoelectric power supply is stored in a capacitor, which supplies it to the detonator when the warhead impacts the target.

- It is actuated by the burning of the propellant.
- It requires the use of temperature sensitive elements/alloys, which makes the unit costly.

Turbo-Generator

It comprises an electric generator assembly housed within a projectile. The assembly includes an air driven turbine and an electric generator. A common shaft carries the turbine and the permanent magnet of the electric generator. The generator rotor is a small permanent magnet and the stator a series of coils. The principle of power generation is similar to the wind turbine-generator unit except that the turbo generator assembly is very compact and operates at substantial rotational speed.

- The impellers used in prior art electrical generators were very inefficient in which most of the air taken in by the turbine is diverted rather than used to drive the impeller.
- The prior art turbines were placed outside the fuze ogive resulting in increased size of the projectile.
- The new developments in the case of the turbo- generator have resulted in reducing the size of the fuze by incorporating the unit inside the fuze ogive.
- The next generation turbo generator power supply makes use of an efficient turbine (centrifugal unit).
- The next generation turbo generator has improved dynamic balance than the prior art generators.
- Since it has a life span equal to that of the whole fuze, and other advantages as mentioned above, it has turned out to be the choice for the next generation electronic fuze.

BASIC CONSTRUCTION OF TURBO-GENERATOR AND AIR INTAKE VALVE

Turbo generator consists of the following components and sub-assemblies modeled in CATIA V5:

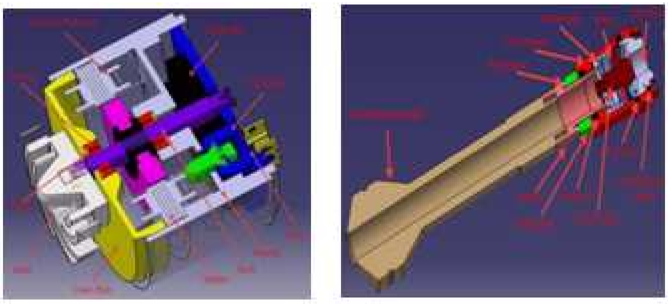

Figure 1: (a) Sectional View of Turbo-Generator (b) Air Intake Valve

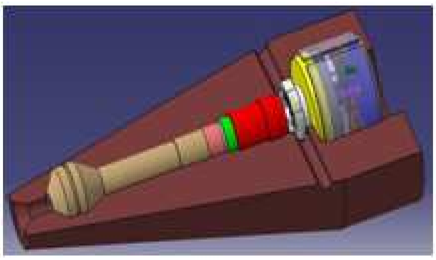

Figure 2: 3D Assembly of Turbo-Generator & Air Intake Valve

DESIGN CALCULATION

Shaft Design Check

Shaft diameter: 2.98 mm.

Shaft material: BS 970 Grade 304, cold worked (EN 58-)

Table 1: Properties of BS 970 Gr 304[2]

Sr.No.	Properties	Value
1.	Density(kg/m^3)	7900
2.	Young's Modulus(Gpa)	200
3.	Specific Heat Capacity(J/kg-K)	500
4.	Ultimate tensile strength(MPa)	680
5.	Yield tensile strength(Mpa)	500
6.	Possion's ratio	0.31

Using ASME code, we have:

$\tau_{(permissible)}$ = min (0.3* S_{yt}, 0.18* S_{ut}) = min (150, 122.4)

= 122.4Mpa

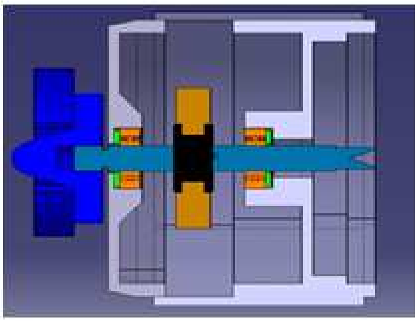

Figure 3: Sectional View of Turbo-Generator for Shaft Design

Structural Analysis

The total forces acting on the shaft can be categorized into 2 groups:

- **Direct Forces:** generated due to the weights of the individual components.
- **Shear Forces:** due to the torque generated by rotation of turbine.

Direct Forces

Assuming the weights of the individual components acting at their individual centre of gravity, the FBD can be represented as:

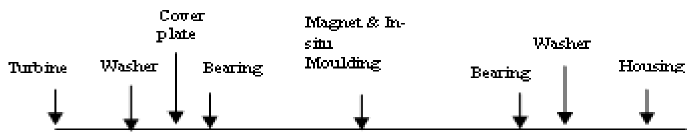

Table 2: Weight of Turbo-Generator Components

Sr. No.	Component Name	Material Density (kg/m^3)	Volume[3] (m^3)	Mass (kg)	Weight (N)
1.	Turbine	1140[4]	6.978*10^{-7}	7.9549*10^{-4}	7.8037*10^{-3}
2.	Washer	8450[8]	1.178*10^{-8}	9.9541*10^{-5}	9.7649*10^{-4}
3.	Cover plate	2770[5]	1.438*10^{-8}	3.9833*10^{-3}	0.03907
4.	Magnet	6900[6]	5.223*10^{-7}	3.6038*10^{-3}	0.03539
5.	In-situ Moulding	1140[4]	1.169*10^{-7}	1.3326*10^{-4}	1.3073*10^{-3}
6.	Housing	2770[5]	4.869*10^{-6}	0.013487	0.1323

Shear Forces

For turbine the starting Torque value of the impeller is kept as low as possible so that it can start early and most importantly can work at higher Altitudes (~30 km) where atmospheric density drops to nearly 1.5% of MSL value and projectile speed is least of the trajectory. From the graph obtained during testing of the Turbo-generator shown as Figure 4 we observe that the starting and hence the running pressure of the turbine can be accounted close to 1 bar. [7]

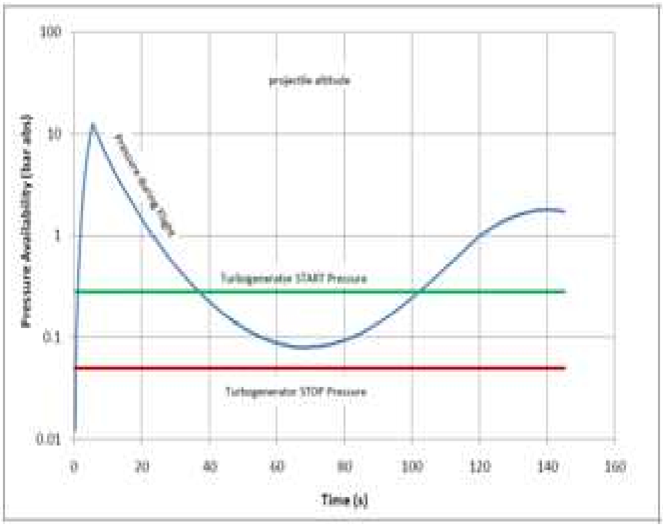

Figure 4: Pressure Availability Curve above Stop Pressure Line Means Continuous Operation during Full Projectile Flight Path [7]

Hence the net force on the blade will be = pressure*area here, pressure=1 bar and area= $2.262*10^{-5}$ m^2 [3]. Therefore force acting per blade= 2.262N Torque pre blade= force*radius= 2.262*10.41 =23.547Nmm

Total torque acting on shaft= 235.474Nmm

The above 2 forces are used to do a detailed analysis in ANSYS. The results are obtained as:

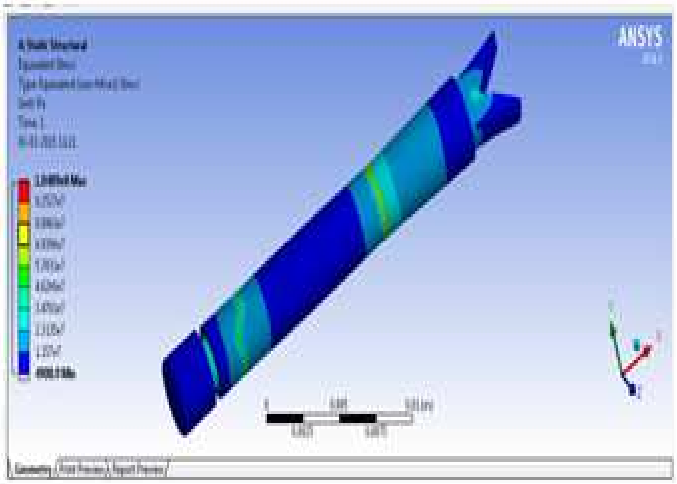

Figure 5: Von-Mises Stress

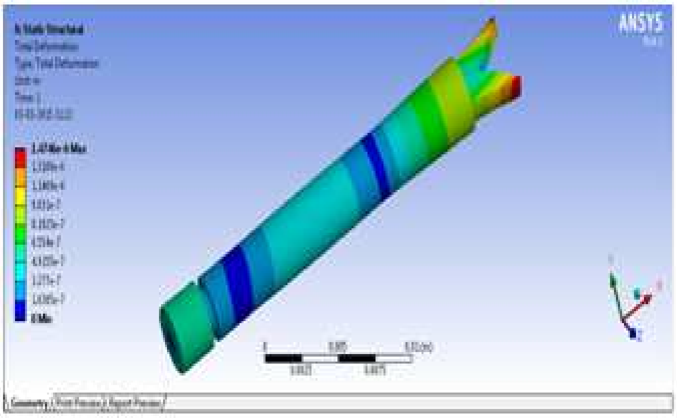

Figure 6: Total Deformation

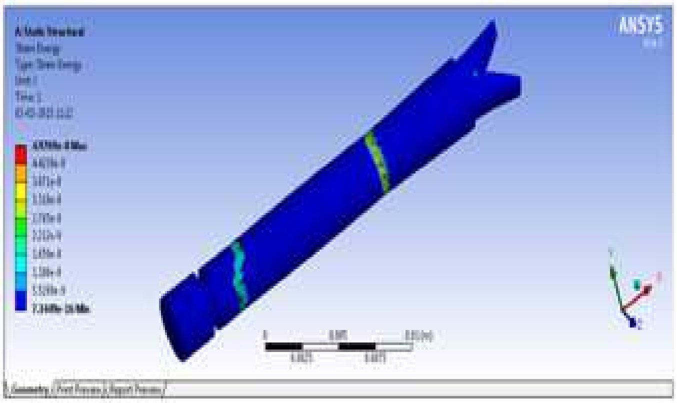

Figure 7: Strain Energy

Therefore from the above results it is seen that the equivalent stress is 104.09MPa<122.Mpa. By using Von-Mises stress criterion the design is safe.

Vibrational Analysis

The angular speed corresponding to the first node is given by: $\omega = (g/\delta)^{0.5}$,

Where:

g=gravitational acceleration=9.81 (m/s^2)

δ=total deformation (m) =$1.4746*10^{-6}$ (m)

ω= angular speed (rad/s)

$\omega= (9.81/1.4746*10^{-6})^{0.5}$ =2579.273 rad/s.

N=60* $\omega/(2*\pi)$=24630.247 rpm**.**

Thus to avoid the sudden failure of shaft due to node formation the speed of 24630 rpm must be avoided which is observed during the projectile speed of 580-620 m/s.

Turbine Design Check

WORKBENCH 14.5 module of ANSYS software is used to carry out the static structural analysis of the turbine.

Specification [9]

Speed range: 125 to 700 m/s.

Altitude range: 6000 to 15000 m.

Material: NYLON6-6.

Table 3: Properties of NYLON6-6[4]

Material Properties	Value
Density	1.14 (kg/m^3)
Young's Modulus	$3.1*10^9$ Pa
Bulk Modulus	$5.1667*10^9$ Pa
Shear Modulus	$1.107*10^9$ Pa
Poisson's ratio	0.4
Tensile yield strength	9.0e07 Pa
Compressive yield strength	9.2e07 Pa
Shear Strength	6.89e07 Pa

Calculation

When the projectile travels through the atmosphere at supersonic speeds, it sets up a normal shock wave in front of it. The air pressure just in front of the projectile and air entering in inlet is represented by P2. At subsonic speeds no shock wave is formed & air pressure just in front of the projectile and air entering in inlet is equal to P1.During supersonic operation the generator, inside the projectile ogive, is exposed to a total pressure at the ogive air inlet equal to P2[11]. Pressure P2 is determined by the flight Mach number and altitude expressed by the Equation 1:

$$\boldsymbol{P2} = \frac{\left\{\left[\frac{k+1}{2}\times M^2\right]^{\frac{k}{k-1}}\right\}}{\left\{\frac{2k}{k+1}\times M^2 - \frac{k-1}{k+1}\right\}^{\frac{1}{k-1}}} \times \boldsymbol{P1}$$

Equation 1: (U.S. Patent No. 4,581,999)

Where:

P2 = free stream static pressure at a given flight altitude;

M=projectile velocity expressed in terms of the local Mach number;

k =1.4 (k is the ratio of specific heat capacities for air).

For a given flight Mach number and altitude, the corresponding pressures of P2 and P1 determine the amount of ram air mass flow that enters the generator, and thus the amount of electrical energy generated.

Since the missile behaves like a projectile the missile will attain its maximum velocity at the launch where P1 will be atmospheric pressure. Considering standard atmospheric conditions from ISA chart we have:

Pressure=1.01325 bar

Temperature: 288.15K

Density of air= 1.225kg/m^3

Speed of sound=340.294 m/s.

The projectile with the increasing velocity and pressure build up at the launch will also experience a temperature rise which is given by the Equation 2[4]:

$$T_0 = T \times \left(1 + \frac{\gamma - 1}{2} \times M^2\right)$$

Equation 2: Stagnation Temperature

Using the above 2 equations we obtain the values of turbine rpm and pressure experienced by turbine and temperature rise is given in tabulated from in the Table 4:

Table 4: Pressure & Temperature Variation Due to Projectile Velocity

Projectile Velocity(m/s)	Mach no.	Turbine rpm [9]	Angular Speed (rad/s)	Pressure (bar)	Temperature (°C)
350	1.02941	54314.43	5687.793	1.985	76.219
400	1.17647	48564.203	5085.631	2.37037	94.915
425	1.25	44492.59	4659.253	2.58999	105.196
450	1.32353	40843.973	4277.171	2.82623	116.102
500	1.47058	34526.547	3615.611	3.34621	139.783
575	1.69117	26823.814	2808.983	4.24022	179.976
650	1.91176	20613.068	2158.595	5.2666	205.779
700	2.0588	17094.709	1790.154	6.02322	259.424

The above parameters are used to carry a detailed analysis of the turbine in ANSYS.

Table 5: Stress Induced In Turbine for Various Projectile Velocities

Projectile Velocity(m/s)	Mach no.	Turbine rpm	Angular Speed (rad/s)	Pressure (bar)	Temperature (°C)	Max Principal Stress(Pa)
350	1.02941	54314.43	5687.793	1.985	76.219	2.27E+07
400	1.17647	48564.203	5085.631	2.37037	94.915	2.63E+07
425	1.25	44492.59	4659.253	2.58999	105.196	2.13E+07
450	1.32353	40843.973	4277.171	2.82623	116.102	3.06E+07
500	1.47058	34526.547	3615.611	3.34621	139.783	3.57E+07
575	1.69117	26823.814	2808.983	4.24022	179.976	4.47E+07
650	1.91176	20613.068	2158.595	5.2666	205.779	5.52E+07
700	2.0588	17094.709	1790.154	6.02322	259.424	6.30E+07

From the results shown in Table 5 it can be seen that the maximum stresses obtained are for 700 m/s. Hence the results are shown for this value:

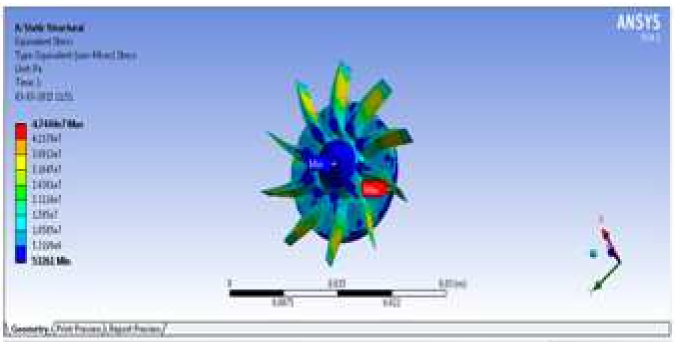

Figure 8: Von- Mises Stress

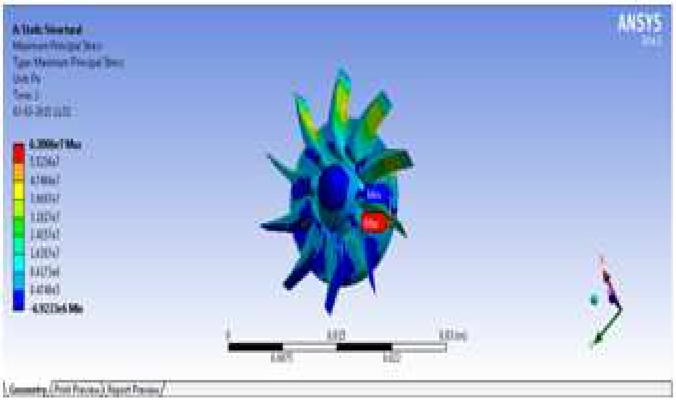

Figure 9: Maximum Principal Stress

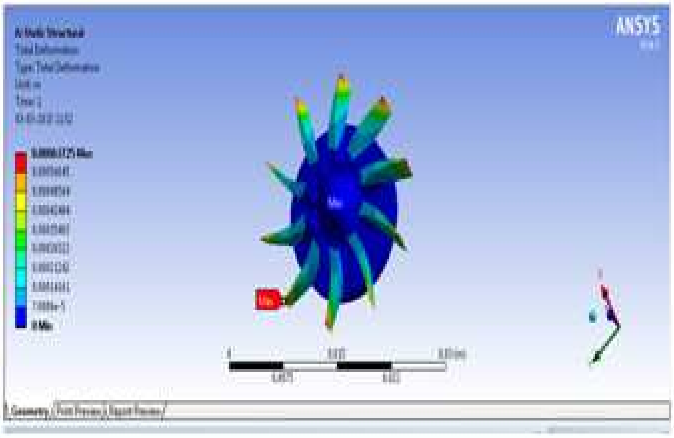

Figure 10: Total Deformation

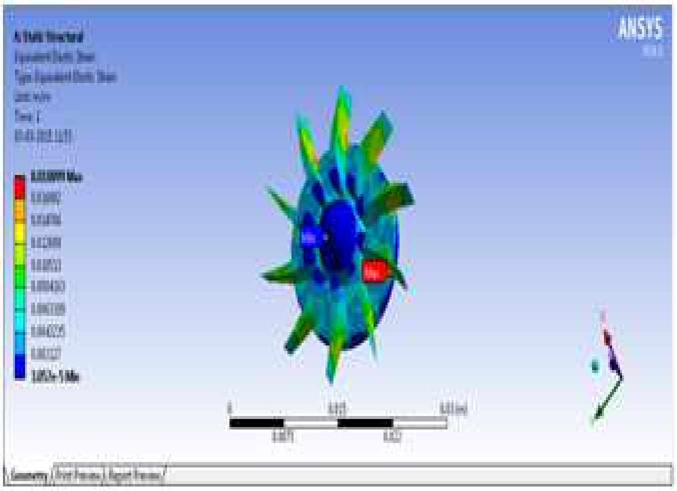

Figure 11: Equivalent Elastic Strain

From the above results the maximum principal stress and the Von-Mises stress (4.7e7, 6.3e7) Mpa < 9e07 Mpa Hence the design is safe.

Magnet Selection

$T_0 = 259.424°C$

This is the maximum temperature rise during the projectile operation, which is obtained at highest operating speed i.e. 700 m/s as shown in Table 5. The different components have to be designed according to the above temperature constraint.

Table 6: Properties of Magnetic Material [10]

Material	Maximum Energy Product Bhmax (MGOe)	Residual Flux Density Br(G)	Coercive Force Hc(Koe)	Working Temperatu – re °C
Ceramic 5	3.4	3950	2400	400
Sintered Alnico 5	3.9	10900	620	540
Cast Alnico 8	5.3	8200	1650	540
Samarium Cobalt 20	20	9000	8000	260
Samarium Cobalt 28	28	10500	9500	350
Neodymium N45	45	13500	10800	80
Neodymium 33UH	33	11500	10700	180

From the characteristics given in Table 6 on the basis of maximum temperature ceramic 5, sintered alnico 5 and cast alnico is suitable for our use. But ceramic being brittle it is excluded. From sintered and cast alnico, sintered alnico has a better cost to strength ratio; hence we select sintered alnico 5 as our choice of our magnet material.

SUMMARY AND CONCLUSIONS

The critical components of turbo generator that are the shaft and turbine have been analyzed using ANSYS Workbench 14.5 module and following conclusions have been drawn:

Von-Mises stress induced in the shaft is of the order 104.09 MPa as against its strength of 122.2 MPa; But, for further increase in power generated, pressure is needed to be increased, which would require redesign & reanalysis of turbine. Vibrational analysis of shaft shows that first node of shaft is obtained at 24630 rpm, that is obtained for the projectile speed in the range of 580-620 m/s. Hence for preventing vibrational failure, prolonged exposure of the projectile at this speed must be avoided. Turbine analysis has been done successfully up till 2.06 mach, and results show that it can sustain much larger pressures.

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