CHOOSE FOCUS ANALYSE (CFA) EXERCISE

ANALYSIS OF *HYDRO PUMP* (MEGA BLASTOISE)

BT5051 Transport Phenomena in Biological Systems
Independence Semester 2025
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Contents

1 Abstract

This report applies the principles of fluid mechanics and transport phenomena to assess the physical plausibility of Mega Blastoise's "*Hydro Pump*". By solving the Bernoulli and continuity equations with appropriate loss coefficients, and assumptions the required internal pressure, flow characteristics, and energy demands are quantified. The analysis reveals the high power requirements and damage done to opponent Pokémon by the move *Hydro Pump*.

2 Introduction

Blastoise (Figure 2.A) is a Generation I Water-type Pokémon native to the Kanto region. Its evolved form, Mega Blastoise (Figure 2.B), obtained through the use of the "Blastoisinite," is capable of channeling immense hydraulic power through its cannon system to perform its signature move, *Hydro Pump* [1].

According to the official Pokédex, "*The cannon on its back is as powerful as a tank gun. Its tough legs and back enable it to withstand the recoil from firing the cannon.*" [2]

From a bioengineering standpoint, this statement is profoundly intriguing. The idea that a biological organism can generate a water beam with the momentum of a tank shell and withstand the recoil forces is fascinating. It raises several questions: How powerful must the water jet be to justify such a description? What internal physiological adaptations would be required to produce and sustain such pressures? Most intriguingly, what would be the resulting impact on the target subjected to this tremendous outflow?

The objective of this study is to examine the biological plausibility of such a mechanism using principles of transport phenomena. By applying fluid mechanics and energy balance concepts, Mega Blastoise's *Hydro Pump* is analyzed as a high-velocity jet system, focusing on its flow characteristics, energy demands, and potential physical effects on both itself and its target.

Figure 2.A - Blastoise

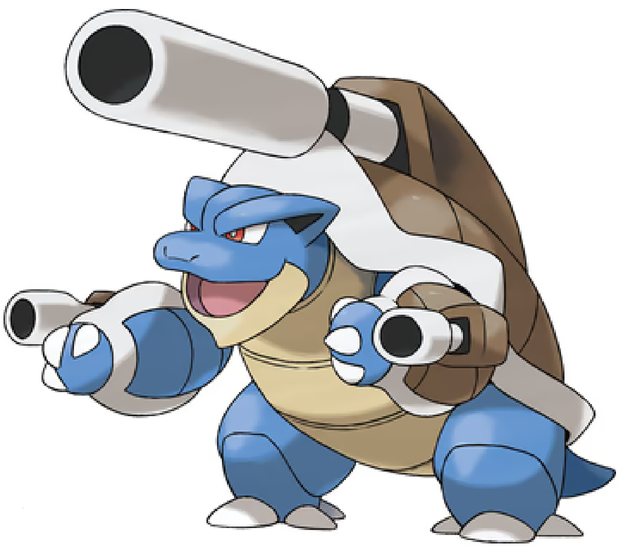

Figure 2.B - Mega Blastoise

3 Analysis

3.1 Volume Estimation

To estimate the volume of water expelled during a single use of *Hydro Pump*, it is first necessary to evaluate the internal volume of Blastoise's shell. The overall dimensions of the shell are illustrated in Figure 3.A.

The approach involves identifying the largest cross-section of the shell and using its geometry as a reference to express the cross-sectional area as a function of length along the shell. Integrating this area function over the total shell length then yields the approximate volume.

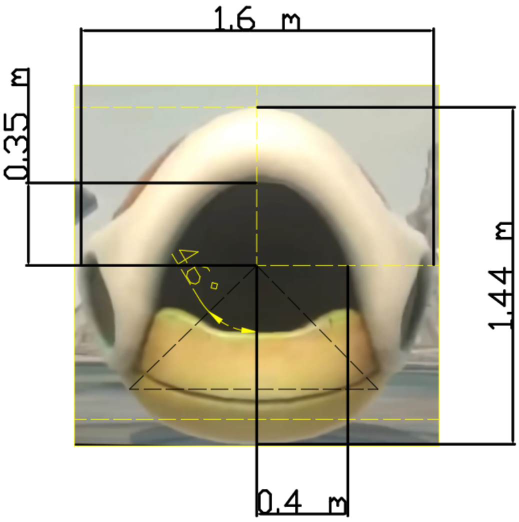

Figure 3.A - Shell Dimensions
(Width is nearly equal to it's height, other dimensions scaled accordingly)

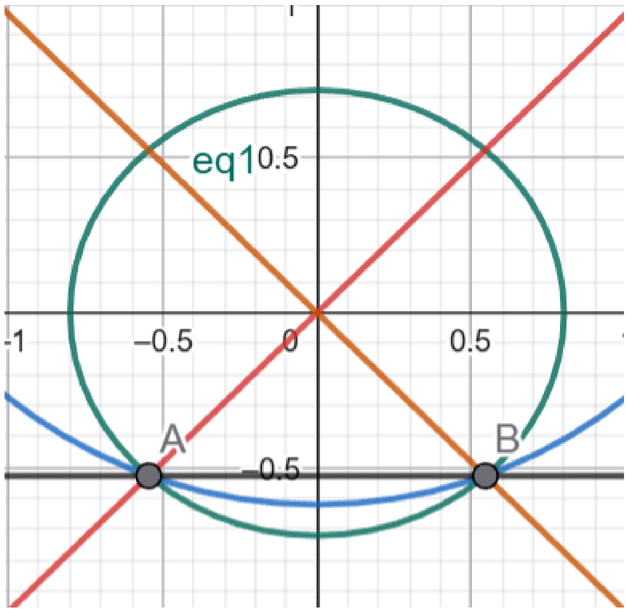

Figure 3.B - Shell Approximation

For the purpose of this calculation, the carapace (upper portion of the shell) is assumed to be ellipsoidal, while the plastron (lower portion) is considered circular, with a much larger radius, passing through the points A and B in Figure 3.B. This geometric simplification allows for an analytically tractable estimation of the total cross-sectional area.

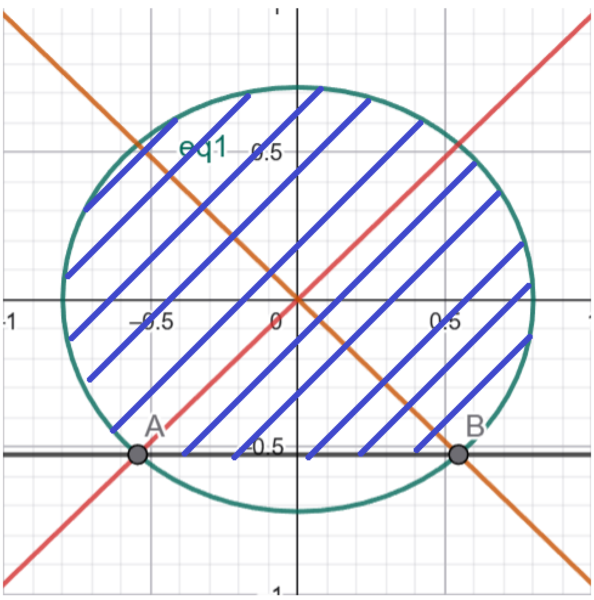

Figure 3.C - Cross Section 1

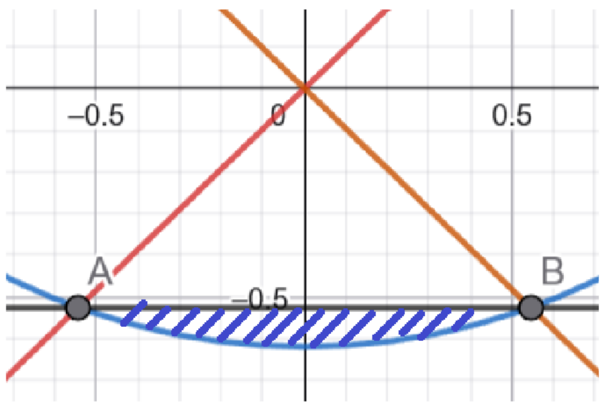

Figure 3.D - Cross Section 2

The division of the shell into two distinct cross-sectional regions is illustrated in Figure 3.B, while Figures 3.C and 3.D depict the individual shaded regions corresponding to the carapace and plastron, respectively.

3.1.1 Computation of Elliptical Cross-Section Area ($\mathrm{CS_1}$)

Given the ellipse:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1, \tag{3.1.1.a}$$

where $a = 0.8$ and $b = 0.72$.

The area of the top half of the ellipse is

$$A_{\text{top}} = \frac{\pi ab}{2} = 0.905 \text{ m}^2.$$

To evaluate the shaded region between $y = y_0$ and $y = 0$ (note that $y_0 < 0$), we use the parametric width at any y:

$$x = \pm a\sqrt{1 - \frac{y^2}{b^2}}.$$

Hence,

$$dA = 2a\sqrt{1 - \frac{y^2}{b^2}}\, dy = \text{width}(y)\, dy.$$

The area of the lower segment is therefore:

$$A = \int_{y_0}^{0} 2a\sqrt{1 - \frac{y^2}{b^2}}\, dy.$$

The total area of cross-section $\mathrm{CS_1}$ is then:

$$A_{\mathrm{CS_1}} = A + \frac{\pi ab}{2}.$$

Let

$$y = b\sin t \quad \text{and} \quad dy = b\cos t\, dt.$$

Then:

$$A = 2a\int \sqrt{1 - \sin^2 t}\,(b\cos t)\, dt = 2ab\int \cos^2 t\, dt.$$

Now,

$$\cos^2 t = \frac{1 + \cos(2t)}{2},$$

so:

$$A = ab\int (1 + \cos(2t))\, dt = ab\left[t + \frac{\sin(2t)}{2}\right]_{t_0}^{0},$$

where $t = \arcsin(\left(\frac{y}{b}\right))$.

Substituting back:

$$A = ab\left\{\arcsin\left(\frac{y}{b}\right) + \frac{1}{2}\sin\left[2\arcsin\left(\frac{y}{b}\right)\right]\right\}_{y_0}^{0}.$$

Evaluating,

$$A = -ab\left\{\arcsin\left(\frac{y_0}{b}\right) + \frac{1}{2}\sin\left[2\arcsin\left(\frac{y_0}{b}\right)\right]\right\}.$$

For $a = 0.8,\ b = 0.72,\ y_0 = -0.72 \times 0.72 = -0.5184$:

$$A = (0.8)(0.72)\,(0.821 + 0.499) \approx 0.76 \text{ m}^2.$$

Thus,

$$\boxed{A_{\mathrm{CS_1}} = 1.67 \text{ m}^2.} \tag{3.1.1.b}$$

3.1.2 Computation of Circular Segment Area ($\mathbf{CS_2}$)

For the circular region, to ensure the plastron is much flatter than the carapace, when offset the center of the circle to (0,1) and set radius $r = 1.62m$, thus ensuring it passes through the points A,B in Figure 3.B where the plastron and carapace meet, the area is therefore computed as the area of the triangle removed from the area of the section of the circle.

$$\text{Area of section} = \frac{\pi r^2 (40)}{360},$$
$$\text{Area of triangle} = r^2 \sin(20°) \cos(20°).$$

Hence,

$$A_{\text{CS}_2} = r^2 \left[\frac{\pi(40)}{360} - \sin(20°)\cos(20°) \right].$$

Thus,

$$\boxed{A_{\text{CS}_2} = 0.028r^2 \approx 0.08 \text{ m}^2.} \tag{3.1.2.a}$$

3.1.3 Total Cross-Sectional Area

From Equation(3.1.1.b) and Equation(3.1.2.a)

$$\boxed{A_{\text{total}} = A_{\text{CS}_1} + A_{\text{CS}_2} = 1.75} \tag{3.1.3.a}$$

3.1.4 Total Volume

Following this, we assume that:

1. The total length of Blastoise is $L = 1.6$ m (as noted in the Pokédex). We assume that the shell spans this entire length.
2. The cross-sectional area of the shell, denoted CS, varies along the body length according to a quadratic profile:
$$CS = aL^2 + bL + c.$$

The following boundary conditions are applied:

- Symmetry about the midline implies that:
$$\frac{d(CS)}{dL} = 0 \quad \text{at } L = 0.8.$$
- The maximum cross-sectional area occurs at $L = 0.8$:
$$CS = 1.75 \text{ m}^2 \quad \text{at } L = 0.8.$$
- At the head/tail ends ($L = 0$), both the semi-major and semi-minor axes are halved, so the area reduces to one-fourth of the maximum:
$$CS = \frac{1.75}{4} = 0.4375 \text{ m}^2 \quad \text{at } L = 0 \text{ (or) } L = 1.6.$$

Under these assumptions:

$$\begin{cases} a(0.8)^2 + b(0.8) + c = 1.75, \\ a(0)^2 + b(0) + c = 0.4375, \\ 2a(0.8) + b = 0. \end{cases}$$

From the second condition:

$$c = 0.4375.$$

Substituting into the first:

$$0.64a + 0.8b = 1.3125.$$

Using $b = -1.6a$ (from the third condition):

$$0.64a + 0.8(-1.6a) = 1.3125 \quad \Rightarrow \quad -0.64a = 1.3125$$

Hence:

$$a = -2.05, \qquad b = 3.3.$$

Thus, the final expression for the cross-sectional area is:

$$\boxed{CS = [-2.05L^2 + 3.3L + 0.4375] \quad \mathrm{m}^2} \tag{3.1.4.a}$$

The total volume is obtained by integrating the cross-sectional area along the shell length:

$$V = \int_0^{1.6} (aL^2 + bL + c)\, dL.$$

Evaluating the integral:

$$V = \left[\frac{aL^3}{3} + \frac{bL^2}{2} + cL\right]_0^{1.6}.$$

Substituting numerical values:

$$V = \frac{a(1.6)^3}{3} + \frac{b(1.6)^2}{2} + c(1.6).$$

Therefore:

$$\boxed{V \approx 2.2\ \mathrm{m}^3.} \tag{3.1.4.b}$$

3.1.5 Volume of Water per attack

The shell possesses a finite thickness, and Blastoise itself must be able to fit within it. Hence, only a fraction of the total computed shell volume can be utilized for water storage. For this analysis, we assume that 70% of the total shell volume is effectively available for water retention.

Additionally, the move *Hydro Pump* is assigned five Power Points (PP), indicating that it can be used five times per battle before Blastoise needs to recharge.

Taking both these factors into account:

$$\text{Effective volume} = 2.2\ \mathrm{m}^3 \times 0.7 \approx 1.5\ \mathrm{m}^3, \tag{3.1.5.a}$$

$$\text{Volume of water per } \textit{Hydro Pump} = \frac{1.5\ \mathrm{m}^3}{5} = 0.3\ \mathrm{m}^3. \tag{3.1.5.b}$$

3.2 Flow Characterization

Our interpretation of the Pokédex statement- *"The cannon on its back is as powerful as a tank gun. Its tough legs and back enable it to withstand the recoil from firing the cannon."*- is founded on a point-blank **momentum** comparison.

While a direct comparison based on kinetic energy would be preferable, it is not realistic to equate a small, hyper-velocity solid projectile (Mach-scale) with a much larger volume of water moving at well-below-Mach speeds. Kinetic energy scales with the square of velocity, so a water jet that matches projectile momentum will generally carry far less kinetic energy than a high-speed penetrator; consequently, momentum is a more appropriate first-order metric for blunt-impact and recoil comparisons in this context.

We adopt the T-90's main gun, the **2A46M 125 mm** smoothbore, as our reference system [3,4]. Taking a representative service round mass of $m = 20$ kg and a muzzle velocity of $v = 1800$ m/s, the point-blank momentum is

$$p \;=\; mv \;=\; 20\ \text{kg} \times 1800\ \text{m/s} \;=\; 36{,}000\ \text{kg} \cdot \text{m/s}. \tag{3.2.a}$$

This is the target momentum we seek to approximate with the *Hydro Pump* model.

We shall assume water is a Newtonian fluid for the following sections. It is known to behave as a Newtonian fluid between 1 MPa to 1000 MPa, at temperatures less than 100°C [5], which is within our bounds.

Now, to classify the type of flow (turbulent or laminar), we shall assume that the entire volume has a uniform velocity v. The fluid properties are taken as:

$$\rho = 998.2071\ \text{kg/m}^3, \qquad \mu = 1.002 \times 10^{-3}\ \text{Pa} \cdot \text{s} \quad \text{(STP conditions)}$$

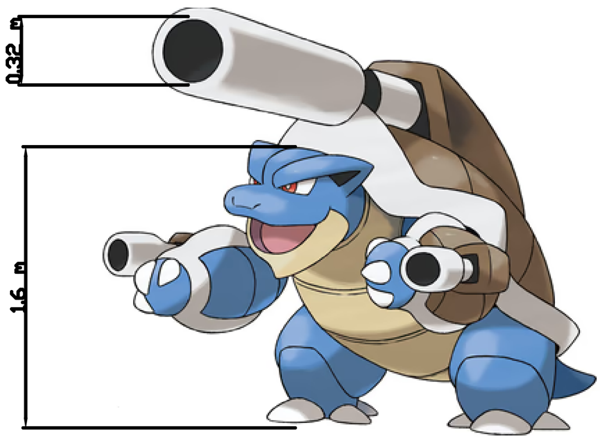

Figure 3.E - Mega Blastoise Cannon Diameter Estimation

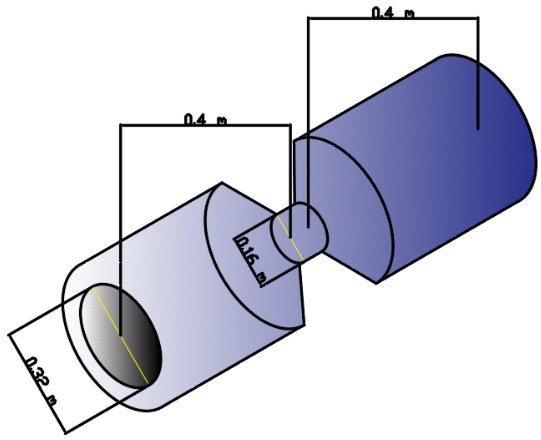

Figure 3.F - Cannon Dimensions

$$(\rho V)\, v = 36{,}000\ \text{kg} \cdot \text{m/s} \tag{3.2.b}$$

$$(998.2071 \times 0.3\ \text{kg})\, v = 36{,}000\ \text{kg} \cdot \text{m/s}$$

$$\therefore \quad v = 120.22\ \text{m/s}$$

The Reynolds number is given by:

$$N_{\text{Re}} = \frac{\rho v d}{\mu} \tag{3.2.c}$$

Substituting the given quantities:

$$N_{\mathrm{Re}} = \frac{(998.2071\ \mathrm{kg/m^3})(120.22\ \mathrm{m/s})(0.3\ \mathrm{m})}{1.002\times 10^{-3}\ (\mathrm{Pa\cdot s})} \approx 3.6\cdot 10^{7} \tag{3.2.d}$$

$$\boxed{N_{\mathrm{Re}} \gg 4000 \quad\Rightarrow\quad \text{As such, the flow is obviously turbulent.}}$$

3.3 Hydro Pump

Remark on the velocity profile. Profile taken from standard turbulent pipe flow (Deissler / 1/7th-power law) [6]; the actual jet at the nozzle exit is expected to be slightly flatter, so this choice is conservative. This choice is supported by claiming the finite delay between the "loading" of the attack and its actual discharge is the phase during which a steady turbulent flow is set up. Under this assumption, it is consistent to use the textbook turbulent profile for the momentum–flux calculation.

3.3.1 Velocity profile and momentum requirement

We assume a turbulent 1/7th–power velocity profile of the form The velocity profile for turbulent flow in a circular section is assumed to follow the one–seventh–power law:

$$\bar{v}_z = k\left(1-\frac{r}{R}\right)^{1/7}, \tag{3.3.1.a}$$

where k is a constant equal to the maximum (centerline) velocity, i.e.

$$\bar{v}_{z,\mathrm{max}} = k.$$

$\bar{v}_z$ is called the time-smoothed velocity, i.e. the average of v_z over a time interval large enough with respect to the time of turbulent oscillation, but small enough with respect to the time changes in the pressure drop causing the flow.

$$\bar{v}_z = \frac{1}{t_a}\int_t^{t+t_a} v_z\,dt \tag{3.3.1.b}$$

The mean (cross–sectionally averaged) velocity is defined as

$$\bar{v}_{z,\mathrm{avg}} = \frac{\displaystyle\int_0^R \bar{v}_z\,(2\pi r)\,dr}{\pi R^2}. \tag{3.3.1.c}$$

Substituting the profile,

$$\bar{v}_{z,\mathrm{avg}} = \frac{2k}{R^2}\int_0^R \left(1-\frac{r}{R}\right)^{1/7} r\,dr.$$

Let $t = 1-\frac{r}{R}$, so that $dr = -R\,dt$ and $r = R(1-t)$. Then

$$\bar{v}_{z,\mathrm{avg}} = \frac{2k}{R^2}\int_{t=1}^{0} t^{1/7}R(1-t)(-R\,dt) = 2k\int_0^1 t^{1/7}(1-t)\,dt.$$

Expanding the integrand,

$$\bar{v}_{z,\mathrm{avg}} = 2k\int_0^1 (t^{1/7}-t^{8/7})\,dt.$$

Integrating term by term,

$$\bar{v}_{z,\mathrm{avg}} = 2k\left[\frac{t^{8/7}}{8/7}-\frac{t^{15/7}}{15/7}\right]_0^1 = 2k\left(\frac{7}{8}-\frac{7}{15}\right).$$

Simplifying,

$$\bar{v}_{z,\text{avg}} = 14k\left(\frac{1}{8} - \frac{1}{15}\right) = 14k\left(\frac{7}{120}\right) = \frac{98k}{120} = \frac{49k}{60}.$$

Hence,

$$\boxed{\bar{v}_{z,\text{avg}} = \frac{49}{60}\,k \;\approx\; 0.817\,\bar{v}_{z,\text{max}}} \tag{3.3.1.d}$$

To match the reference point–blank momentum of

$$(\rho V)\,\bar{v}_{z,\text{avg}} = 36{,}000 \text{ kg m/s},$$

and taking the discharge volume for one attack as $V = 0.30$ m^3, we have

$$\rho\,\frac{49}{60}\,k = \frac{36{,}000}{0.30} = 120{,}000 \quad \Rightarrow \quad \rho\,\frac{49}{60}\,k = 120{,}000. \tag{3.3.1.e}$$

Solving for k gives the parametric form

$$k = \frac{120{,}000 \times 60}{49\,\rho}. \tag{3.3.1.f}$$

3.3.2 Engineering Bernoulli Equation

$$\frac{\Delta p}{\rho} + \frac{\Delta v^2}{2} + g\Delta x + \hat{F}_L + \hat{W}_s = 0, \tag{3.3.2.a}$$

and take

$$\Delta p = p_{\text{out}} - p_{\text{in}}, \qquad \Delta v^2 = 0, \qquad \Delta x = 0, \qquad \hat{W}_s = 0.$$

Therefore,

$$\frac{p_{\text{out}} - p_{\text{in}}}{\rho} + \hat{F}_L = 0 \quad \Rightarrow \quad p_{\text{in}} - p_{\text{out}} = \rho\,\hat{F}_L. \tag{3.3.2.b}$$

The cannon is idealised as

- a long inlet pipe of diameter $D_1 = 0.32$ m and length $L_1 = 0.40$ m,
- a sudden contraction to diameter $D_2 = 0.16$ m,
- a sudden expansion to diameter $D_1 = 0.32$ m,
- a long exit pipe of diameter $D_2 = 0.16$ m and length $L_2 = 0.40$ m.

The area ratio is therefore

$$\frac{A_2}{A_1} = \left(\frac{D_2}{D_1}\right)^2 = \left(\frac{0.16}{0.32}\right)^2 = \left(\frac{1}{2}\right)^2 = \frac{1}{4}, \tag{3.3.2.c}$$

so the velocity in the small section is

$$v_2 = \frac{A_1}{A_2}\,\bar{v}_{z,\text{avg}} = 4\,\bar{v}_{z,\text{avg}} = 4 \cdot \frac{49}{60}k = \frac{196}{60}k. \tag{3.3.2.d}$$

(i) Long linear segment (clubbing together both inlet and exit pipes). Using the friction factor from the Moody chart ($f = 0.006$ for a smooth pipe at $Re \approx 3.6 \times 10^7$),

$$\hat{F}_{L,1} + F_{L,4} = 4f\,\frac{L_1}{D_1}\left(\frac{49}{60}k\right)^2.$$

With $L_1 = 0.40$ m, $D_1 = 0.32$ m:

$$4f\,\frac{L_1}{D_1} = 4(0.006)\frac{0.40}{0.32} = 0.024 \times 1.25 = 0.03, \tag{3.3.2.e}$$

so

$$\hat{F}_{L,1} = 0.03\left(\frac{49}{60}k\right)^2. \tag{3.3.2.f}$$

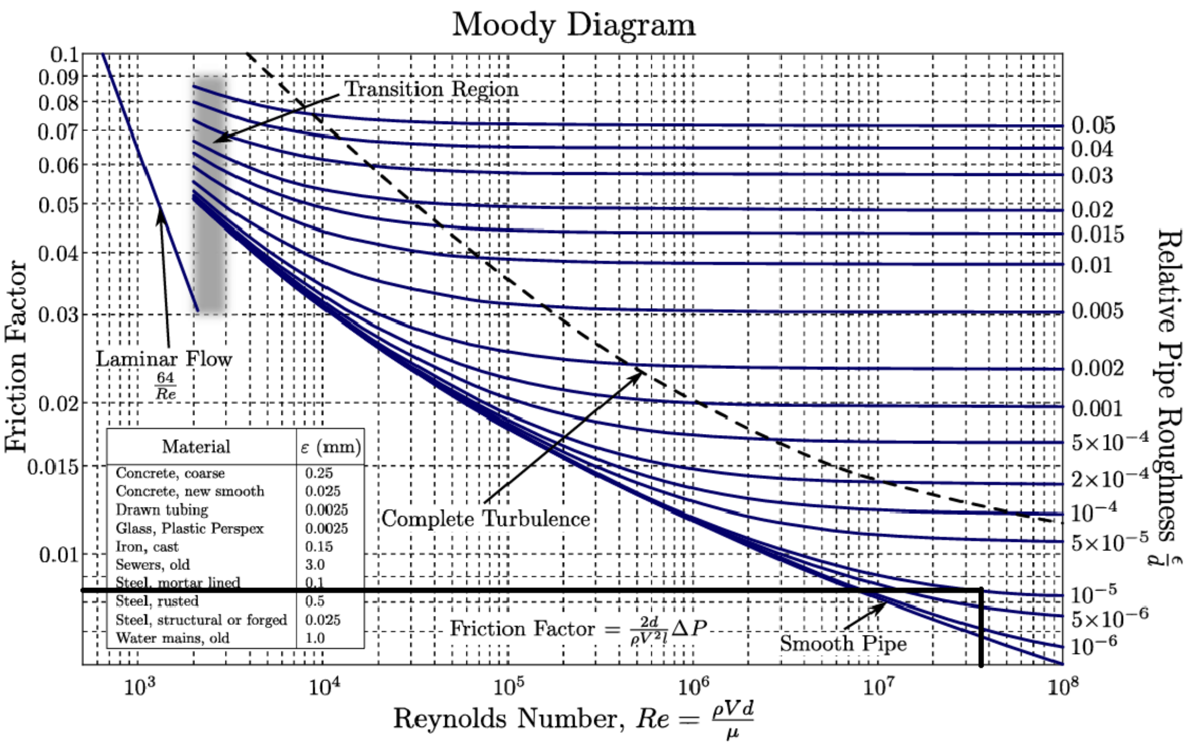

Figure 3.G -Moody Chart for obtaining fricition factor

(ii) Sudden contraction. We take the standard coefficient

$$K_f = 0.4\left(1 - \frac{A_2}{A_1}\right) = 0.4\left(1 - \frac{1}{4}\right) = 0.4(0.75) = 0.30.$$

Hence

$$\hat{F}_{L,2} = K_f\,\frac{v_2^2}{2} = 0.15\left(\frac{196}{60}k\right)^2. \tag{3.3.2.g}$$

(iii) Sudden expansion. For the expansion,

$$K_f = \left(1 - \frac{A_1}{A_2}\right)^2 = \left(1 - \frac{1}{4}\right)^2 = (0.75)^2 = 0.5625,$$

and therefore

$$\hat{F}_{L,3} = K_f\,\frac{v_2^2}{2} = 0.28125\left(\frac{196}{60}k\right)^2. \tag{3.3.2.h}$$

Total loss. Adding Equation(3.3.2.f), Equation(3.3.2.g), and Equation(3.3.2.h)

$$\begin{aligned}\hat{F}_L &= (0.15 + 0.28125)\left(\frac{196}{60}k\right)^2 + 0.03\left(\frac{49}{60}k\right)^2 \\ &= 0.43125\left(\frac{196}{60}k\right)^2 + 0.03\left(\frac{49}{60}k\right)^2.\end{aligned}$$

Thus,

$$\boxed{\hat{F}_L \approx 4.622\,k^2.} \tag{3.3.2.i}$$

Substituting Equation(3.3.2.i) into Equation(3.3.2.b),

$$p_{\text{in}} - p_{\text{out}} = \rho\,(4.622\,k^2) \quad\Longrightarrow\quad p_{\text{in}} = \rho\,4.622\,k^2 + p_{\text{out}}. \tag{3.3.2.j}$$

Taking $p_{\text{out}} = p_{\text{atm}} = 1.01325 \times 10^5$ Pa:

$$\boxed{p_{\text{in}} = \rho \cdot\ 4.622\,k^2 + 1.01325 \times 10^5.} \tag{3.3.2.k}$$

3.3.3 Relation between Density and Pressure

To obtain a relation for density vs pressure;

$$\rho = \frac{m}{V}; \quad \text{(Assuming constant mass, and differentiating both sides)} \tag{3.3.3.a}$$

$$d\rho = -\frac{m}{V^2}\, dV \quad \Rightarrow \quad \frac{m}{V} = \rho \tag{3.3.3.b}$$

$$d\rho = -\frac{\rho}{V}\, dV \quad \Rightarrow \quad \frac{d\rho}{\rho} = -\frac{dV}{V} \tag{3.3.3.c}$$

To use to solve numerical eqn

$$\frac{\Delta\rho}{\rho} = -\frac{\Delta V}{V} \tag{3.3.3.d}$$

We know Bulk modulus (B) [7]

$$B = -\frac{\Delta P}{\Delta V / V} \tag{3.3.3.e}$$

$\therefore$ This ΔP is not the same as the one from Engineering Bernoulli eqn. This $\Delta P = (P_i - P_{i-1})$

$$\text{Now } \frac{\Delta V}{V} \text{ can be expressed as } -\frac{\Delta\rho}{\rho}$$

$$B = \frac{\Delta P}{\Delta\rho/\rho} \quad \Rightarrow \quad B\,\Delta\rho = (\Delta P)\,\rho$$

$$\Delta\rho = \left\{\rho_i \cdot \frac{\Delta P}{B}\right\}$$

$$\boxed{\rho_{i+1} = \rho_i + \left\{\frac{\rho_i\,\Delta P}{B}\right\}} \tag{3.3.3.f}$$

3.3.4 Simple Fixed Point Iteration, and Time of Firing

From Equation(3.3.1.f), Equation(3.3.2.k), and Equation(3.3.3.f)

$$(i) \quad k = \frac{120{,}000 \times 60}{49\,\rho}$$

$$(ii) \quad P_i = 4.622\,k^2\,\rho + 1.01325 \times 10^5$$

$$(iii) \quad \rho_{i+1} = \rho_i + \left\{\frac{\rho_i\,(P_i - P_{i-1})}{B}\right\}$$

iterating until convergence (using fixed point iteration, Refer to the Appendix for the code) we get ;

$$\rho = 1041.6 \text{ kg/m}^3; \quad P = 946.56 \text{ atm}; \quad k = 141.07 \text{ m/s}$$

$$\tau = \text{time of firing} = \frac{V}{\bar{V}_{z,\text{avg}}\,A} \tag{3.3.4.a}$$

$$\tau = \frac{0.3 \times 60}{(49)(141.07)(\pi)(0.16)^2} \text{ s}$$

$$\boxed{\tau = 32.4\,\text{ms}} \tag{3.3.4.b}$$

3.4 Effect on Mega-Blastoise

3.4.1 Energy and Power Requirement

Work done:

$$W = P(\Delta V) = 0.3 \text{ m}^3 \times 9.59 \times 10^8 \text{ Pa} \tag{3.4.1.a}$$

$$\boxed{W = 2.877 \times 10^7 \text{ J} \approx 28.77 \text{ MJ}} \tag{3.4.1.b}$$

Power required:

$$\boxed{\dot{W} = \frac{28.77 \times 1000}{32.4} \approx 888 \text{ MW}} \tag{3.4.1.c}$$

3.4.2 Recoil Impulse and Force Experienced

Mega–Blastoise weighs approximately 101.1 kg according to its Pokédex entry.

From momentum conservation,

$$\text{Impulse imparted} = 36{,}000 \text{ kg} \cdot \text{m/s}$$

Hence, we expect a recoil velocity of approximately $v_r = 356$ m/s, this velocity is super sonic, however to mitigate this mega blastoise is known to anchor itself to the ground in some cases before using *Hydro Pump*. As such it is more reasonable to analyse the average force experienced, since even its Pokédex entry claims it's "*tough legs and back enable it to withstand the recoil from firing the cannon*".

Figure 3.H -Mega Blastoise anchoring itself, prior to the use of *Hydro Pump*

Thus, the average recoil force experienced by Mega–Blastoise is:

$$\boxed{F_{\text{avg}} = \frac{p \text{ (Impulse)}}{\tau} = \frac{36{,}000 \times 1000}{32.4} = 1.11 \text{ MN}} \tag{3.4.2.a}$$

3.4.3 Quantifying these values through real world values

- It requires roughly $\sim 4{,}000$ N of force to fracture a typical human femur [8]. If Mega–Blastoise were to receive an equivalent momentum impulse directly with *no* recoil, and its skeletal structure consisted of ordinary biological materials, the resulting load would produce catastrophic structural failure. Thus, unless the creature's bones are composed of an unusually high-strength (non-biological) material, absorbing such an impulse without severe damage is physically implausible.

- A typical commercial nuclear reactor generates approximately 1 GW of electrical power, equivalent to 10^9 J/s [9]. Even though I considered it to be impossible it turns out that Mega–Blastoise's cannon would have an energy release comparable to that of a high-performance military cannon.

3.5 Effect on Opponent Pokémon

For this final section, we will need the dimensions of the Pokémon Battlefield. However, this is not standard; therefore, we assume that the battlefield is as large as a soccer stadium (supported by the side-by-side images of both, shown in Figures 3.I and 3.J, respectively).

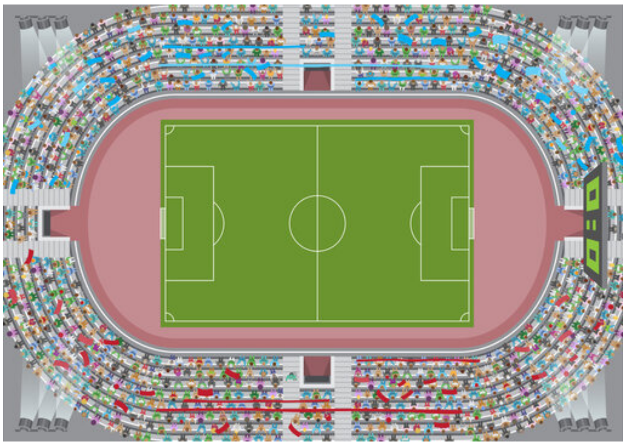

Figure 3.I - Soccer Stadium

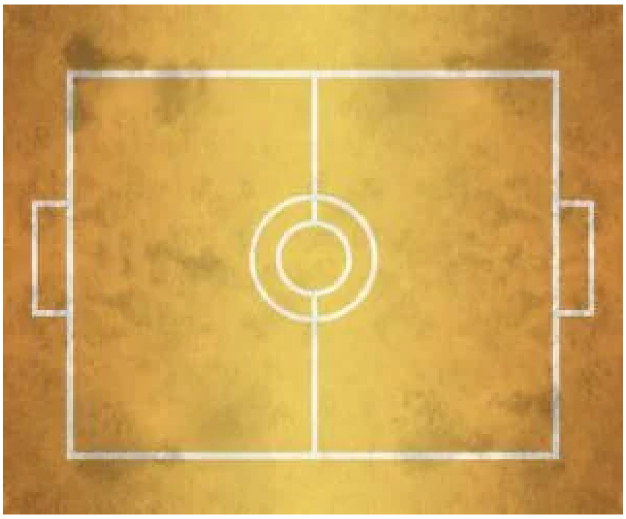

Figure 3.J - Pokémon Battlefield

We set up the problem as shown below

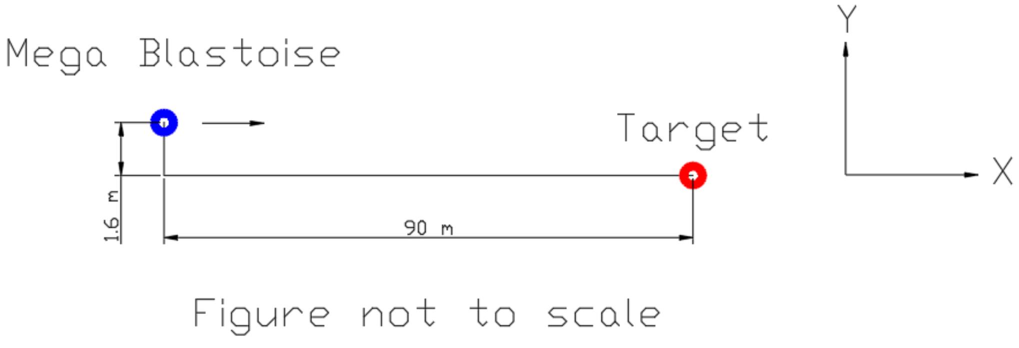

Figure 3.K -Visualizing the attack in 2D

3.5.1 Projectile Motion with Linear Drag

$$\frac{dv_x}{dt} = -kv_x, \tag{3.5.1.a}$$

$$\frac{dv_y}{dt} = -kv_y - g \tag{3.5.1.b}$$

NOTE: k has the dimensions s^{-1}

3.5.2 Evaluating Time of Flight

$$\int_0^{v_y} \frac{dv_y}{(kv_y + g)} = \int_0^t -dt$$

$$\left[\frac{\ln(kv_y + g)}{k}\right]_0^{v_y} = -t$$

$$\ln\left(\frac{kv_y}{g} + 1\right) = -kt$$

$$e^{-kt} = \frac{kv_y}{g} + 1$$

$$v_y(t) = \frac{g}{k}\left(e^{-kt} - 1\right)$$

$$\frac{dy}{dt} = \frac{g}{k}\left(e^{-kt} - 1\right)$$

$$\int_0^{-1.6} dy = \frac{g}{k}\int_0^T \left(e^{-kt} - 1\right) dt$$

$$-1.6 = \frac{g}{k}\left[\frac{e^{-kt}}{-k} - t\right]_0^T$$

$$-1.6 = \frac{g}{k}\left[\frac{1 - e^{-kT}}{k} - T\right]$$

$$\boxed{T = \left[\frac{1}{k} + \frac{1.6k}{g}\right] - \frac{1}{k}\left(e^{-kT}\right)} \tag{3.5.2.a}$$

3.5.3 Solving for Critical Launch Velocity

$$\frac{dv_x}{dt} = -kv_x$$

$$\int \frac{dv_x}{v_x} = \int -kdt$$

$$\ln(v_x) - \ln(v_0) = -kt$$

$$v_x = v_0 e^{-kt}$$

$$\frac{dx}{dt} = v_0 e^{-kt}$$

$$\int_0^d dx = \int_0^T v_0 e^{-kt} dt$$

$$d = v_0 \left[\frac{e^{-kt}}{-k}\right]_0^T$$

$$kd = v_0\{1 - e^{-kT}\}$$

$$\boxed{v_c = \frac{kd}{1 - e^{-kT}}} \tag{3.5.3.a}$$

3.5.4 If $k = 1$

$$T = 1.16 - e^{-T}$$

$$T = 0.6244 \text{ seconds}$$

$$90 = v_c\{1 - e^{-T}\}$$

$$\boxed{v_c = \frac{90}{(1 - e^{-0.6224})} = 194 \text{ m/s}} \tag{3.5.4.a}$$

At such high dissipation of energy, the attack would not reach the enemy at all.

3.5.5 If $k = 0.1$

$$T = 10.016 - 10e^{-0.1T}$$

$$T = 0.571 \text{ seconds}$$

$$90 = 10v_c\{1 - e^{-T/10}\}$$

$$\boxed{v_c = \frac{90}{10(1 - e^{-0.0571})} = 162.2 \text{ m/s}} \tag{3.5.5.a}$$

The attack still fails to reach the enemy target, let us see why.

3.5.6 Elementary Test

To determine why the critical velocity is so high, consider:

$$T = \sqrt{\frac{2h}{g}} = 0.57 \text{ seconds}, \quad (k = 0) \tag{3.5.6.a}$$

$$R_{\max} = (0.571)(140) = 80 \text{ m} \tag{3.5.6.b}$$

If the two Pokémon are more than 80 m apart, the attack will never hit unless it is fired at an angle (regardless of k).

3.5.7 If $k = 0.1$ and $d = 60$ m

We set up the problem as shown below

From Equation 3.5.2.a, we get $\quad T = 10.016 - 10e^{-0.1T}$

$$\boxed{T = 0.571 \text{ seconds}} \tag{3.5.7.a}$$

$$\boxed{v_c = \frac{60 \times 0.1}{(1 - e^{-0.0571})} = 108.1 \text{ m/s}} \tag{3.5.7.b}$$

$$141.07(1 - \frac{r}{R})^{\frac{1}{7}} = 108.1$$

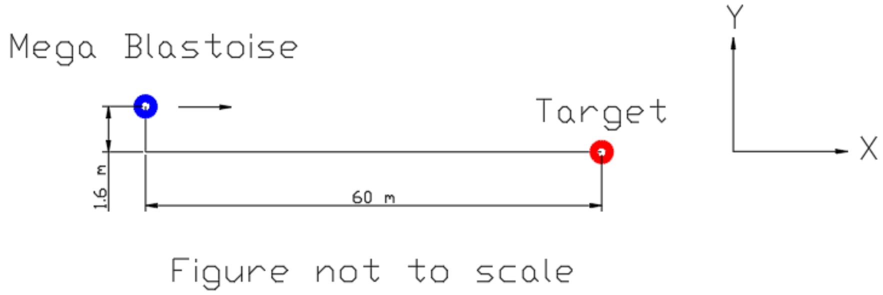

Figure 3.L - Visualizing the attack under new assumptions

$$(1 - \frac{r}{R}) = 0.155$$
$$\frac{r}{R} = 0.845$$
$$\boxed{r_{\text{limit}} = 0.84R} \tag{3.5.7.c}$$

Computing the momentum of the region able to make contact with the opponent Pokémon

$$\overrightarrow{P}_{\text{initial}} = \int \rho\, \bar{v}_z^2\, \tau\, dA$$

$$\overrightarrow{P}_{\text{initial}} = 2\pi\rho\tau \int \bar{v}_z^2\, r\, dr$$

$$\overrightarrow{P}_{\text{initial}} = 2\pi\rho\tau(141.07)^2 \int_0^{r_{\text{lim}}} \left(1 - \frac{r}{R}\right)^{2/7} r\, dr \tag{3.5.7.d}$$

Let $t = (1 - \frac{r}{R})$, hence $dr = -R\, dt$:

$$\overrightarrow{P}_{\text{initial}} = -2\pi\rho\tau(141.07)^2 R^2 \int t^{2/7}(1-t)\, dt$$

$$\overrightarrow{P}_{\text{initial}} = -2\pi R^2\rho\tau(141.07)^2 \int (t^{2/7} - t^{9/7})\, dt$$

$$\overrightarrow{P}_{\text{initial}} = -2\pi R^2\rho\tau(141.07)^2 \times 7 \left[\frac{t^{9/7}}{9} - \frac{t^{16/7}}{16}\right]$$

$$\overrightarrow{P}_{\text{initial}} = -14\pi R^2\tau\rho(141.07)^2 \left[\frac{(1-\frac{r}{R})^{9/7}}{9} - \frac{(1-\frac{r}{R})^{16/7}}{16}\right]_0^{0.84R} \tag{3.5.7.e}$$

Substituting limits:

$$\overrightarrow{P}_{\text{initial}} = -14\pi R^2\tau\rho(141.07)^2 \left[\frac{(0.16)^{9/7} - 1}{9} + \frac{1 - (0.16)^{16/7}}{16}\right]$$

Simplifying:

$$\overrightarrow{P}_{\text{initial}} = 14\pi R^2\tau\rho(141.07)^2[0.1 - 0.062]$$

$$\overrightarrow{P}_{\text{initial}} = 14\pi R^2\tau\rho(141.07)^2[0.038]$$

$$\boxed{\overrightarrow{p}_{\text{initial}} = 28735 \text{ kg} \cdot \text{m/s}} \tag{3.5.7.f}$$

Since ρ and τ are constants, it follows that

$$Impulse \propto \bar{v}_z^2$$

but $\bar{v}_z$ decays exponentially:

$$\bar{v}_z = \bar{v}_{z,\text{initial}} e^{-kt}$$

Hence:

$$\frac{|\overrightarrow{p}_{\text{initial}}|}{|\overrightarrow{p}_{\text{final}}|} = \frac{1}{[1 - e^{-kt}]^2} \tag{3.5.7.g}$$

Ideally, this would require a complex integral to solve, since not all parts of the beam connect at the same time.
To side-step this, we take:

$$t = \frac{60}{\bar{v}_{z,\text{avg}}} = 0.53 \text{ sec} \tag{3.5.7.h}$$

The final momentum before contact is thus

$$\overrightarrow{P}_{\text{final}} = [28735] \left\{ (1 - e^{-0.1(0.53)})^2 \right\} \tag{3.5.7.i}$$

$$\boxed{\overrightarrow{P}_{\text{final}} \approx 77 \text{ kg} \cdot \text{m/s}} \tag{3.5.7.j}$$

And the force imparted is

$$\boxed{\text{Impulse} = 77 \text{ kg} \cdot \text{m/s}}$$

$$\boxed{\text{Force imparted} = \frac{77 \times 1000}{32.4} = 2376 \text{ N}}$$

The force exerted is abysmally low compared to the immense energy required to launch the attack. A professional boxer can deliver over 4000 N of force sustained over a longer impact duration, resulting in significantly greater damage while expending only a fraction of the energy Mega Blastoise consumes.

Despite its intimidating description, the Hydro Pump's actual impact is relatively harmless, even to an ordinary human—owing to the extremely brief contact time and the modest magnitude of force applied during that interval.

---

4 Conclusion

The modeled system demonstrates that Mega Blastoise's Hydro Pump would demand nearly 946 atm of pressure and release 0.3 m^3 of water per attack at about 140 m/s, yielding a recoil force of approximately 1.1 MN. Such immense power and energy levels are comparable to modern nuclear reactor outputs, far exceeding biological feasibility.

However, despite the immense energy expenditure and physiological strain on Mega Blastoise, the actual physical damage inflicted on the opposing Pokémon is comparatively negligible—rendering Hydro Pump an inefficient and self-taxing move whose toll on the user far outweighs its destructive impact.

A more rigorous analysis could be undertaken by incorporating advanced pressure–density correlations and dynamic impact modeling that account for variations in contact time and deformation effects. Nevertheless, this report serves as a comprehensive preliminary framework, providing a strong foundation for future studies that wish to explore the mechanics of such high-energy biological jet systems in greater depth.

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5 Acknowledgement

I would like to sincerely thank the course instructor Dr. G. K. Suraishkumar for providing this opportunity to apply the principles and techniques taught in class to a problem I found to be intriguing, even if not necessarily grounded in reality.

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7 Appendix

The code for solving Equation(3.3.1.f), Equation(3.3.2.k), and Equation(3.3.3.f) using simple fixed point iteration.

```
den = 998.2071
B = 2.2 * (10**9) # Obtained from the cited wikipedia page [7]

k_array = []
den_array = [den,]
P_array = [1.01325*(10**5),]

for n in range(15):

    ki = (120000*60)/(49*den)
    k_array.append(ki)

    Pi = (4.622*(ki**2)*den)+(1.01325*(10**5))
    P_array.append(Pi)

    delP = P_array[-1]-P_array[-2]

    den_next = den + ((den*delP)/B)
    den = den_next
    den_array.append(den)

P_atm = []

for n in P_array:
    P_atm.append(n/(1.01325*(10**5)))

print(k_array[-1],"m/s")
print("="*50)
print(P_array[-1],"Pa")
print("="*50)
print(den_array[-1],"kg/m^3")
print("="*50)
print(P_atm[-1],"atm")
print("="*50)
```

The output generated is given below

```
141.07128194212532 m/s
==================================================
95910030.08128211 Pa
==================================================
1041.5924027009687 kg/m^3
==================================================
946.5584019864999 atm
==================================================
```