A Preliminary Assessment of Inducing Anthropogenic Tropical Cyclones Using Compressible Free Jets and the Potential for Hurricane Mitigation

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Abstract. We have conceptually studied the potential for mitigation of natural hurricanes by inducing anthropogenic perturbations prior to or in front of an advancing hurricane. We propose actual hardware for the task. It consists of multiple jet engines mounted on barges or ships that will be dispatched to strategic locations in the ocean where the sea surface temperature is high and the vertical temperature profile and atmospheric conditions are such that the potential for development of a hurricane or tropical storm is high. The engines will direct compressible high momentum, high-speed free jets skyward causing entrainment of even larger amounts of additional air to form plumes and updrafts. The unstable humid updraft will itself produce conditions for additional entrainment and evolution of tropical cyclones. These anthropogenic perturbations will extract enthalpy from the ocean, cooling the ocean surface and depriving the advancing natural hurricane of its needed thermal energy.

The barrage of hurricanes and adverse impacts on human life and property in the Southeastern United States and Caribbean Basin during 2004-2005 has revived an interest in hurricane mitigation (Hoffman 2004, 2002). Reputable atmospheric scientists have developed a few ideas for hurricane mitigation over the past 60 years (Gray et al. 1976; Simpson 1981). Only two programs have involved actual field or laboratory experiments (Willoughby et al. 1985; Alamaro 2001). The most well known was the Stormfury project that lasted for more than 20 years, under which NOAA used cloud seeding by silver iodide to try to nucleate supercooled water in the hurricane's clouds. The hypothesis was that the heat of fusion released upon nucleation would increase the hurricane eyewall diameter, leading to a decrease in the maximum wind speed. Through radar observations it was eventually discovered that the clouds contain ice and little or no supercooled water, so the project was abandoned (Willoughby et al. 1985). Another attempt was undertaken at the Air-Sea Interaction Laboratory at the Massachusetts Institute of Technology, where a monolayer film was used to retard evaporation in a wind wave tank in which the airflow over the water surface was comparable to that of hurricane (Alamaro 2001). The hypothesis was that spreading a monolayer film on the ocean in the front of the hurricane would retard the evaporation that fuels the hurricane with latent heat. Unfortunately, at a wind speed of about 10 m/sec or higher the film tends to break apart and becomes immersed in the water due to high-speed airflow and wave action, and loses its effectiveness (See: http://alamaro.home.comcast.net/Evaporationretardation.htm).

We propose to induce atmospheric perturbations in front of or prior to an advancing hurricane or potentially dangerous cyclone. These induced perturbations will extract enthalpy from the ocean surface, leading to a decrease in the sea surface temperature (SST). As such, the approaching naturally occurring hurricane will be deprived of its source of enthalpy. It is hypothesized that the hurricane intensity will then be much reduced prior to landfall.

Compressible free jets generated by multiple jet engines mounted on barges or ships will induce the perturbations. They will be dispatched to strategic locations in the ocean during an advancing hurricane. Alternatively, the jet generator vessels will continuously patrol the western Tropical Atlantic, inducing cyclones during the hurricane season to reduce the SST up to a few hundred miles from the shoreline.

The proposed method is analogous to backfires created by firefighters when confronting an advancing firewall. Small and controlled fires are started in front of the advancing, uncontrolled and larger fire. By the time the main fire advances, its fuel supply has been consumed causing it to be reduced in intensity and if properly executed, extinguished. Just as firefighters maintain distance between the backfires and the larger fire so they do not merge, it would be necessary to keep a distance between the induced cyclones and the natural hurricane so they do not merge to form a larger hurricane.

Compressible Free Jets and Plumes. A free jet is an unbounded flow of one fluid into another and is generated by pressure difference at the orifice of the jet. A plume is an updraft of air due to buoyancy forces (Lee and Chu 2003). Free jets are usually turbulent and turbulent mixing causes transport of momentum, energy and species to the surrounding fluid. The effective mass transfer rate of the jet is increased with the distance from the jet orifice due to entrainment as its velocity is reduced. The momentum flux of a free jet is preserved during entrainment.

The airspeed in the updraft of a hurricane is on the order of 1-10 m/sec. We have concluded that generating such incompressible low airspeed by a free jet is impractical since to achieve a substantial air mass flow and momentum a fan of impractical large cross sectional area would be required. Moreover, the momentum flux imparted to a jet is proportional to the square of its speed and as a result the mass rate of the entrained air is proportional to the square of the initial jet speed.

Therefore, we suggest the use of a compressible high-speed free jet generated by surplused, retired or decommissioned jet engines. For example, a Pratt & Whitney JT3D-3B jet engine that was used to power airplanes such as the Boeing 707, or its military equivalent the TF33-3 engine that was used to power the B-52 provide roughly 50,000 N of thrust, with an air mass flow of approximately 110 Kg/sec and a compressible free jet speed is about 460 m/sec. Twenty such jet engines mounted on a barge will provide a total momentum flux of about 10^6 N. By the time the entrained jet airspeed decreases to 10 m/sec and subsequently to 1.0 m/sec the ascending entrained air mass will have reached a flow rate of 10^5 Kg/sec and 10^6 Kg/sec, respectively. This ascending air mass rate is due to the initial momentum provided by the jet engines and does not include plumes. It is roughly 3-4 orders of magnitude smaller than the ascending air mass in the updraft of fully developed hurricane[1]. It is expected that if this is done at locations where the SST is higher than 26^0C - 27^0C, where the atmosphere is humid and the gradients along height of potential temperature is negative causing instability, the free jet will eventually grow to produce large and unstable plumes and updrafts of tropical storm or hurricane proportions.

The approximated chemical reaction of combustion in the jet engine is:

$$CH_2 + 3/2\ O_2 = H_2O + CO_2$$

The combustion gas excluding nitrogen (which is not affected by the combustion) and unburned oxygen is a mixture of water vapor and carbon dioxide, the molecular weight of which is 31, slightly heavier than that of air. Since the ratio of combustion gas to air in the jet of turbofan jet engine is small, it is not expected that the increase in the molecular weight of the jet will impede its upward motion. Turbulent mixing with ambient air would result in an immediate reduction of the jet density approaching that of the ambient air. Furthermore, injection of water in the high temperature jet will add water vapor to the jet and increase the humidity of the entrained air, increasing the buoyancy.

Implementation. We conceptually studied two scenarios for implementation of the proposed technology. In the first, the natural hurricane's path is predicted. Barges towed by ships as shown in Figure 1 carry the jet engines and fuel, and are dispatched in the Western Tropical Atlantic or the Caribbean, westward of the advancing hurricane. Because there is always some uncertainty about the track of a hurricane that is traveling westward, multiple free jet facilities will be situated in rows that are generally extended from south to north to account for any deviation from the predicted path of the hurricane.

The power and total energy of a tropical storm is less than the power and total energy of a hurricane. The power of moving air is proportional to the cube of its velocity. If the air speed of a tropical storm is (¾) that of a hurricane, the power per unit area of the ocean surface of a hurricane is approximately $1/(3/4)^3$ or four times that of a tropical storm. In this example it will be required that approximately four tropical storms travel in front of a hurricane, and deprive it of enthalpy intake. Therefore, multiple tropical storms are required in advance of the advancing hurricane.

[1] An order of magnitude estimate for the mass rate of updraft air in a hurricane has been calculated based on the following approximations: Total power of a hurricane 10^{12} -10^{13} Watt. This estimate enables to find the rate of water vapor ascending using the latent heat of evaporation approximated as 2.5 10^6 J/kg. From knowing the rate of water vapor ascending and the water vapor density over SST at 27 Degree Celsius and assuming 100% relative humidity, we can arrive with an estimate for the rate of ascending air.

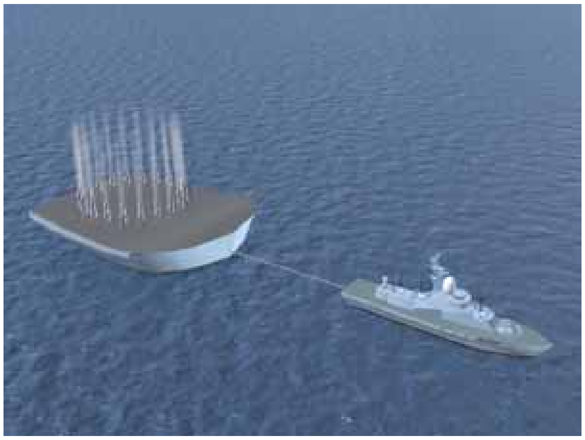

Fig. 1: Artistic view of multiple jet engines directing jet skyward for inducing anthropogenic atmospheric perturbations

Logistically, this scenario may be difficult to execute since once a hurricane is evolved there is not much time to determine where the barges should be dispatched, and for actual dispatching of the barges and free jet implementation. Even if successful, it may be possible that multiple tropical storms would reach the shoreline causing high winds and flooding. This, combined with the inherent uncertainties of the outcome of weather modification and the lack of confidence that indeed the induced cyclones will alter the trailing hurricane, may lead to an erosion of public support for the hurricane mitigation program.

In an alternative scenario, the SST of the ocean up to a distance of a few hundred miles from the shoreline will be kept lower by a few degrees during the hurricane season. For that, barges or ships equipped with compressible free jet systems will continuously patrol the oceans and be dispatched to locations where the SST is high. The initiation of tropical storms in this case will be done in advance of the evolution of hurricanes. The timing of the generation of anthropogenic tropical storms may include, in addition to hurricane mitigation, the requirements for rainfall at specific regions on land and the potential landfall locations of the hurricane. As more experience is gained, the proper spatial and temporal distribution of the anthropogenic storms can be developed to optimize effects and to avoid landfall of multiple storms at one location during a short period of time.

The preferred mode of operation in this case is the following: The first anthropogenic tropical storms will be initiated as close as possible to the shoreline regardless of an existing or advancing natural hurricane. By the time these induced man-made cyclones arrive on shore their intensity will be minimal and it is possible that they will decay before arriving on shore. At the same time or afterward, a second row of barges will start a second row of tropical cyclones Eastward of the initial row. The second row of cyclones will travel westward and eventually will travel over lower SSTs that had been caused earlier by the first row. At the same time or afterwards a third row of tropical cyclones will be started eastward of the second row, and so forth. It may be sufficient to cool the ocean surface by 2-3 degrees Celsius, up to a distance of a few hundred miles from the shoreline, to ensure that an advancing natural hurricane that is formed in the Mid or Eastern Atlantic would travel over lower SSTs, substantially reducing its potentially destructive energy before landfall.

The cost of full scale implementation to protect the Southern US, Caribbean Basin and Central America is estimated at $0.5 –0.75 billion per year. A substantial portion of this budget could be in-kind or overhead contributions by the military and various government agencies.

Atmospheric Conditions. Other or alternative effects and processes resulting from the anthropogenic cyclones may also contribute to the weakening of a natural hurricane as well. For example, the large-scale overturning subsidence associated with the secondary circulation of the anthropogenic storms may suppress convection and increase the vertical shear of horizontal wind in the inner core region of the approaching natural hurricane (Wang and Holland 1995). It is hypothesized that the hurricane intensity may also be reduced by this mechanism prior to landfall. Another possible consequence is the direct interaction between the anthropogenic perturbations and the natural hurricane. Such an interaction could change the track of the hurricane. It is possible that the anthropogenic cyclones could be "designed" to steer the natural hurricane from landfall at highly populated coastal regions or be steered back out to sea and away from any landfall (Hoffman 2004; Y. Wang, 2005 personal communication).

A more general application of anthropogenic modification is to modify the tropical atmosphere where it is most sensitive to small perturbations that will grow in amplitude and scale over several days to the point that some characteristics of a subsequent tropical cyclone will be altered. This does not necessarily involve direct creation of another tropical cyclone. It may instead involve tropical waves or other large-scale features. It may not be possible to entirely prevent a given tropical cyclone, but it might be possible to, for instance, alter the track of the storm slightly so as to miss large population centers or areas prone to devastating storm surge effects or inland flooding (C. Davis, 2005 personal communication). Calculations of sensitivity in the tropics are still in their undeveloped stages and require much better models than exist now, including calculations that are capable of resolving individual cumulus towers (or at least a much improved representation of their effects).

Many calculations of the response of the tropical atmosphere to small perturbations are required to understand what may result from a perturbation of the type envisioned to be created from arrays of jet engines. This study has many practical implications for understanding the sources of errors in dynamic prediction in the tropics, and so carries importance beyond anthropogenic modification scenarios (C. Davis, 2005 personal communication).

In the tropic oceans under direct solar radiation (the sun is not partly or completely covered by clouds) the stratification of the atmospheric layer over the sea surface is rather stable. Figure 2 shows average gradients of potential temperature $\Theta = T(1000/P)^{0.286}$ during 24 hours time, where T is the air temperature in ^{0}K, and P is the atmospheric pressure at the level of measurements. Curve 1 in Figure 2 is for tropical ocean areas. These data were obtained during numerous measurements made on expeditions in the Pacific Ocean and South China Sea (Pudov and Korolev 1990). Positive values for potential temperature gradient indicate stability while negative values indicate instability, a factor that may be necessary for inducing unstable updrafts by the proposed jet. The jet operation, therefore, may better be done at nights and/or in the presence of initial cloudiness of a fraction no less than 6-7.

The higher the relative humidity (f %), the lower the condensation height level where evaporation heat will be released from the ascending humid air. The height of the condensation level (h) can be roughly estimated as h = 22 (100-f %), where h is in meters above surface. For example, for a relative humidity of 80% the condensation level is about 400 meters. To reduce the condensation height it may be necessary to inject water into the exhaust nozzles of the jet engines.

The jet engines might be sufficient for disturbing the stability of the air layer near the water surface in the tropics, especially in the late afternoon or at night. In the extra-tropical zones it may be possible to create convective clouds with the help of vertical jets most of the day.

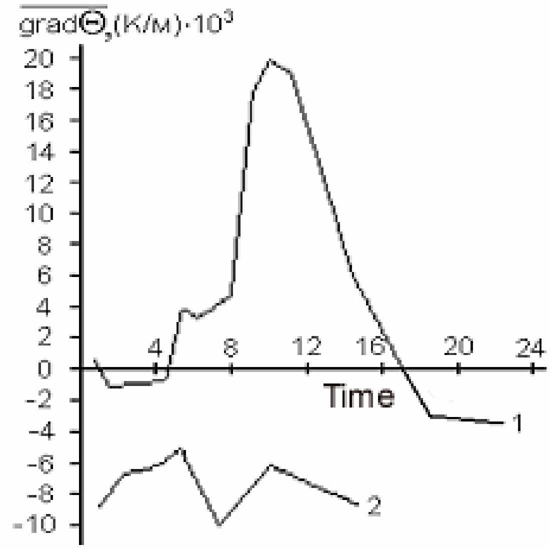

Fig. 2: Gradients of potential temperature along height vs. time; Curve 1 for over tropical ocean; Curve 2 for extra-tropical ocean (Pudov and Korolev 1990).

Legal and Policy Considerations. A report of The National Research Council states: "The Committee concludes that there is still no convincing scientific proof of the efficacy of intentional weather modification efforts." (p. 3). The report also states: "If simple precipitating cloud systems cannot be modified in significant ways, it is very difficult to believe that a strongly organized large dynamic system such as a hurricane can be modified" (NRC 2003).

The fundamental problem of weather modification is that controlled experiments are difficult if not impossible. There is always uncertainty that the outcome of the modification, such as enhancing rainfall, is due to the modification or the natural variability of weather. This uncertainty is less of a problem in this proposal since if a tropical storm is generated consistently a few times after applying jet engines, cause and effect will become clear. Even if a well-supported theory of hurricane modification existed, the legal ramifications of weather modification on this scale are daunting. A few of the many possibilities include (R. Anthes, 2005 personal communication):

1. The storm is not modified at all, but some people perceive that it is, suffer personal damage or injury and file lawsuits.

2. The storm is modified according to theory, but still does significant damage and some people blame the modifiers on the damage,

even though the modification actually reduced overall damage and impact.

3. The modified storm produced “winners” and “losers” and the perceived “losers” sue. For example, what if the hurricane abruptly changed course? The people affected by the new course might well blame the modification effort and sue (R. Anthes, 2005 personal communication).

It is clear that first it would be necessary to further the theory and then to design experiments that do not have the potential to cause harm. Only then it would make sense to develop policy for international treaties to enable implementation under the supervision of international advisory committee, to assure public acceptance of hurricane modification. For example, according to future international treaties, hurricane damage will be compensated regardless if the hurricane has been modified or not. But suing will not be an option.

Pilot Development. Tropical cyclones involve complex fluid dynamic processes, including rotating and stratified flows, boundary layers, air-sea interaction and multiphase thermodynamics (Emmanuel 1991). It is impossible to scale down these processes in a laboratory experiment. The only avenue for development is to test the concept over the high seas. The first milestone would be the creation of an anthropogenic perturbation or tropical storm by a free compressible jet. This may be done anywhere in the ocean outside of the hurricane season, nominally before June or after November, to assure that the induced storm does not become a hurricane, or is perceived to have done so. To assure success of the pilot program we recommend employing as many jet engines as possible in the first trial runs and then to reduce the number if possible.

The projected cost of such a pilot project is estimated to be $25 - $40 million, most of which could be in-kind contributions from government agencies and the military. Old and retired jet engines can be donated by the Air Force for example, at scrap value or less. Airlines may also wish to donate such retired engines in exchange for write-offs against taxable income. Such arrangements can be made with the US Government and others, such as the Russian Government. The cost of a flight-worthy reliable jet engine is substantial but the reliability of the jet engines necessary for this project is not an issue. It would be entirely acceptable if 10 - 30% of the stationary jet engines used for the pilot program and subsequent implementation break down during operation.

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Appendix: Review of Free Jet and Strategies for the Application of Jet Engines

Introduction and definitions

The following is basic information on and calculations for compressible free jets produced by jet engines.

A "Free Jet" is a flow of one fluid into another. The other fluid is a surrounding fluid at rest or in a motion relative to the jet. Walls or ducts do not confine the free jet. The jet flow is impeded only by shear stress with relation to the surrounding fluid.

The term "compressible" does not refer to the fluid of the free jet. For example, the jet can be of air, which is a compressible gas. However, the flow can be compressible or incompressible. In any flow where the Mach Number (M) is less than 0.3 the flow is incompressible. At M > 0.3 the flow is compressible. For air at ambient temperature the flow is incompressible when the air speed is lower than approximately 100 m/sec. Flow from jet engines used in commercial airplanes is usually at about sonic speed so the free jet considered is initially compressible. However the compressible jet velocity is rapidly reduced by entrainment of air that joins the jet, and the free jet becomes in-compressible at a point about 20 meters from the jet engine nozzle.

The following analysis is intended to provide a cloud modeler a fundamental familiarity with the performance of a typical jet engine mounted vertically for cloud formation.

Geometry of circular jet

The schematics below describe the following:

a. Jet engine and a nozzle of diameter d_o and cross sectional area A.

b. Approximately uniform velocity profile or "plug flow" at the jet nozzle.

c. Divergence lines where the flow velocity is half the maximum velocity in the Gaussian profile or the lines of $\overline{U}_{0.5}$.

d. The maximum average velocity $\overline{U}_m$ at the center of the circular Gaussian velocity profile.

e. $\overline{U}_{0.5}(x)$, while x is the distance from the jet nozzle.

f. Flow of entrained air.

Fundamental equations

For a circular jet, the radius at the point where the air velocity in the Gaussian profile is half of the maximum velocity at the same radial distace from the nozzle is given by:

$$r_{\overline{U}_{0.5}} = 0.085 \cdot x \tag{1}$$

The most important property of a free jet is its momentum flux. The momentum flux at the exit from the nozzle is:

$$J = \dot{m}U_0 = \rho_0 \; A U_0^2 \tag{2}$$

Where U_0 is the speed at the exit from the engine which is approximated as uniform, A is the cross sectional area of the nozzle and ρ_0 is the density of the gas. The momentum flux is also equal to the thrust provided by the jet.

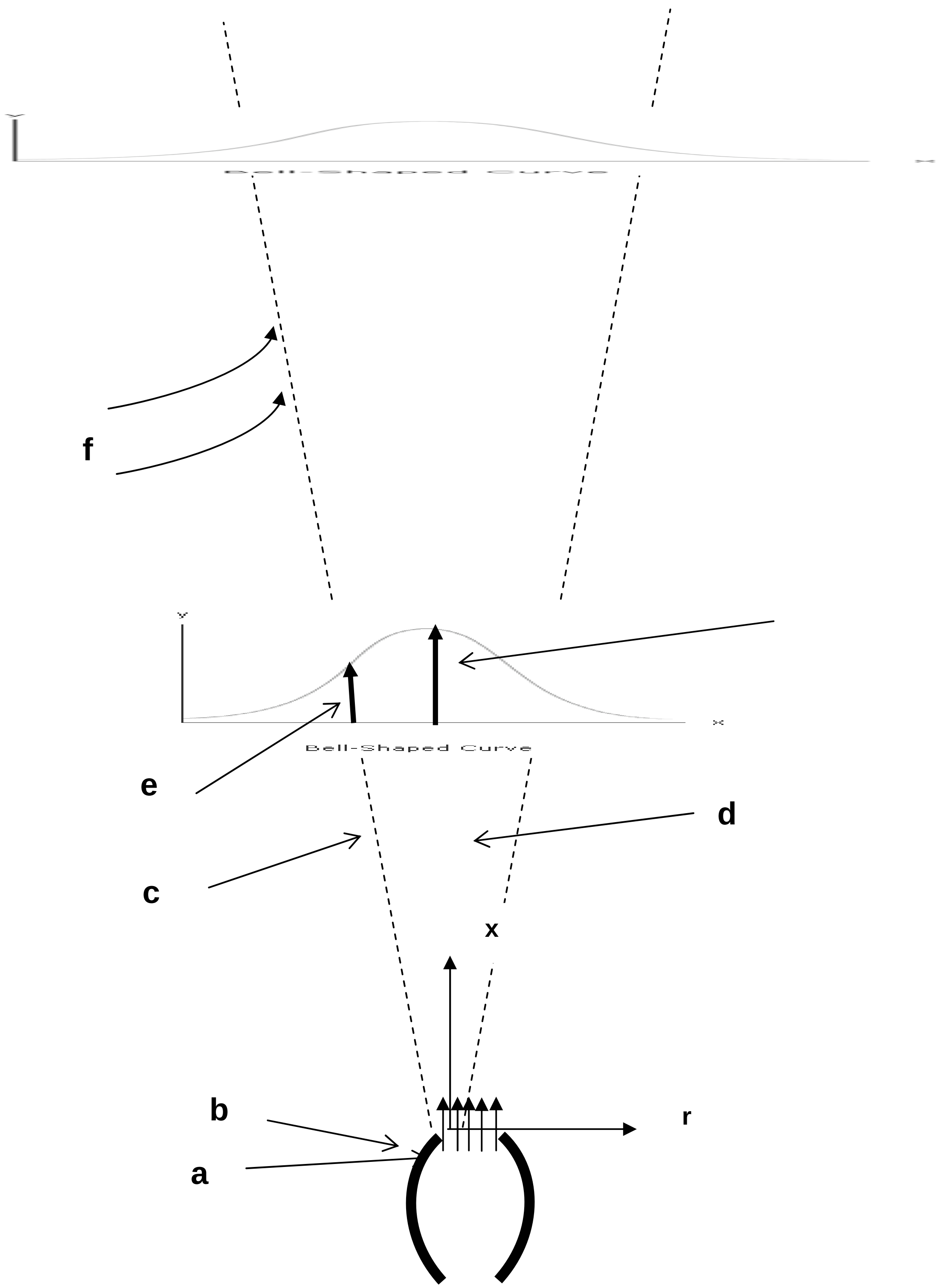

Figure A-1: Free jet schematics

For the vertical jet the cylindrical corrdinates are x and r where x is the height from the center of the nozzle of the jet engine. Assuming that the jet engine operates at sea level, x is also the elevation above sea level.

Using a control volume analysis on the jet that of any arbitrary height x from the jet origin, it is possible to show that the momentum flux of the jet is preserved at any distance from the jet origin. Therefore:

$$J = \rho_0 \ AU_0^2 = 2\pi\rho(x)\int_0^\infty rU^2(x,r)dr = const \tag{3}$$

for any value x.

In eq. (3) the density is a function of the height x and U(x,r) is the gas velocity which has a circular Gaussian velocity profile.

Description and equations of circular jet

The flow exiting from the jet engine nozzle has almost uniform velocity profile and therefore it is called "plug flow". Upon ejection there is shear stress with the surrounding air and therefore its velocity profile changes to a Gaussian profile at a distance of approximately 6-10 of d_0 – diameter of the nozzle. Non-dimensional analysis provides the equations that approximate the subsequent flow:

$$\overline{U}_m(x) = c_2 \cdot \frac{\sqrt{J/\rho(x)}}{x} \tag{4}$$

Where $\overline{U}_m(x)$ is the jet maximum velocity at the centerline, J is the momentum flux defined in (3), $\rho(x)$ is the air density as a function of height x and c_2 is a constant.

The Gaussian velocity distribution is:

$$U(x,r) = \overline{U}_m(x) \cdot \exp\left(\frac{-r^2}{a^2(x)}\right) \tag{5}$$

For a circular jet:

$$a(x) = c_1 \cdot x \tag{6}$$

Ignoring eq. (4) we can derive the expression for $\overline{U}_m(x)$ through the use of equations (3), (5), and (6):

$$J = \rho_0 \ AU_0^2 = 2\pi\rho(x)\int_0^\infty rU^2(x,r)dr = 2\pi\rho(x)\int_0^\infty r\overline{U}_m{}^2 \exp\left(\frac{-2r^2}{c_1^2 x^2}\right)dr =$$

$$= 2\pi\rho(x)\overline{U}_m^2(x)\int_0^\infty r\exp\left(\frac{-2r^2}{c_1^2x^2}\right)dr = 2\pi\rho(x)\overline{U}_m^2(x)\frac{c_1^2x^2}{4} = J \quad (7)$$

Rearranging:

$$\overline{U}_m(x) = \frac{1}{c_1}\sqrt{2/\pi}\,\frac{\sqrt{J/\rho(x)}}{x} \quad (8)$$

Let's define $c_2 = \frac{1}{c_1}\sqrt{2/\pi}$. c_1 has been found empirically to be 0.103 so $c_2 = 7.75$ (Rodi 1975).

Assumptions and a procedure for numerical calculations of circular jet

The assumptions and data used are for a specific single jet engine. The suggested procedure for numerical caculation is provided below.

Step 1

Calculate the initial momentum flux or thrust of the specific jet engine. Assume that the engine is a TF33-3 (that used to power the B-52 bomber and Boeing 707) for which $U_0 = 460\ m/\sec$. Also, assume that the jet produced by the engine is not of a combustion gas but air at the same ambient temperature and pressure as the ambient air at sea level. (These assumptions may be revised in a more rigorous analysis). For T=300 K, at specified barometric pressure and relative humidity we can calculate the density ρ_0 using the equation of state. For purposes of this calculation assume that $\rho_0 = 1.17\ \frac{Kg}{m^3}$. The nozzle diameter is $d_0 = 0.5\ m$. Substituting this into (1):

$$J = \rho_0\ AU_0^2 = 1.17\cdot\frac{\pi}{4}0.5^2\cdot 460^2 \cong 50{,}000\left[Kg\ m^{-3}\ m^2\ m^2\ s^{-2}\right] \cong 50{,}000\ N$$

Step 2

Assign a vertical profile of temperature, pressure, humidity and temperature lapse rate. From this, calculate the density of the air as a function of the height. The height is x_i . Steps can be at 1, 10 or 100 meters. This will be decided by the user.

Step 3

Assume that the jet engines are operated on a ship or a barge in the sea. Assume also that the jet becomes similar (or Gaussian) at x = 20 m. Substitute in eq. (3):

$$\overline{U}_m(x) = c_2\cdot\frac{\sqrt{J/\rho(x)}}{x} = 7.75\cdot\frac{\sqrt{50{,}000/\rho(20)}}{20} \cong 80.1\ m/\sec$$

The last result is significant. It shows that the jet speed has been reduced from 460 m/sec to a Gaussian profile when the maximum speed in the centerline is 80.1 m/sec where the flow becomes incompressible. The initial mass flow rate from the jet engine is:

$$\dot{m}_{engine} = \rho_0 A U_0 = 109 \,\frac{Kg}{\sec}$$

To calculate the mass flow rate of the Gaussian profile at **x = 20 m** using eq. (3), first calculate the velocity profile using eq. (5):

$$U(20,r) = \overline{U}_m(20)\cdot\exp\left(\frac{-r^2}{a^2(20)}\right) = 80.1\cdot\exp\left(\frac{-r^2}{0.103^2\cdot 20^2}\right) = 80.1\cdot\exp\left(\frac{-r^2}{4.244}\right)$$

The mass flow rate $x = 20\ m$ is:

$$\dot{m}(x=20) = 2\pi 80.1\rho(20)\int_0^\infty r\cdot\exp\left(\frac{-r^2}{4.244}\right)dr \cong 588.8\int_0^\infty r\cdot\exp\left(\frac{-r^2}{4.244}\right)dr$$

Use the identity $\int_0^\infty r\cdot\exp\left(\frac{-r^2}{a}\right)dr = \frac{a}{2}$

Therefore:

$$\dot{m}(x=20) \cong 588.8\int_0^\infty r\cdot\exp\left(\frac{-r^2}{4.244}\right)dr = 588.8\cdot\frac{4.244}{2} = 1{,}250\,\frac{Kg}{\sec}$$

The ratio of the mass flow rate of air at x = 20m to the mass flow rate from the jet engine is:
$\dot{m}(20) = 11.46\,\dot{m}_{engine}$

To check the the momerntum flux at x = 20 m:

$$J = 2\pi\rho(x)\int_0^\infty rU^2(20,r)dr = 2\pi\rho(x)\int_0^\infty r\overline{U}_m^2(20)\exp\left(\frac{-2r^2}{c_1^2 x^2}\right)dr =$$

$$= 2\pi\rho_0\,\overline{U}_m^2(20)\int_0^\infty r\exp\left(\frac{-2r^2}{c_1^2 x^2}\right)dr = 2\pi 1.17\cdot 80.1^2\int_0^\infty r\exp\left(\frac{-2r^2}{0.103^2 20^2}\right)dr =$$

$$47{,}162\int_0^\infty r\exp\left(\frac{-r^2}{2.122}\right)dr = 47{,}162\,\frac{2.122}{2} \cong 50{,}000\ N$$ As expected

Example B

Calculate of the speed of the jet and the total mass flow rate due to a single engine at **x** =1,000 m.

The density at x =1,000 m may be calculated as follows:

$$\frac{\rho(1{,}000)}{\rho_0}=\left(\frac{T(1{,}000}{T_0}\right)^{\frac{g}{R_{air}\cdot\mu}-1}\cong\left(\frac{300-6.5}{300}\right)^{\frac{9.81}{287\cdot 6.5 10^{-3}}-1}\cong 0.91$$

At this stage it is required to make assumptions about the necessary atmospheric conditions during cloud formation operation.

$$\rho(1{,}000)=0.91\cdot\rho_0=1.066\frac{Kg}{m^{-3}}$$

$$\overline{U}_m(1{,}000)=c_2\cdot\frac{\sqrt{J/\rho(1{,}000)}}{1{,}000}=7.75\frac{\sqrt{50{,}000/1.066}}{1{,}000}\cong 1.678\ m/\sec=$$

$$=1.678\cdot\exp\left(\frac{-r^2}{0.103^2\cdot 1{,}000^2}\right)=1.678\cdot\exp\left(\frac{-r^2}{10{,}609}\right)$$

The mass flow rate is:

$$\dot{m}(x=1{,}000)=2\pi 1.678\cdot 1.066\int_0^\infty r\cdot\exp\left(\frac{-r^2}{10{,}609}\right)dr\cong 11.24\int_0^\infty r\cdot\exp\left(\frac{-r^2}{10{,}609}\right)dr$$

$$\dot{m}(1{,}000)\cong 11.24\cdot\frac{10{,}609}{2}=59{,}622\frac{Kg}{\sec}=547\dot{m}_{engine}$$

Checking the momentum flux:

$$J=2\pi\rho(1{,}000)\int_0^\infty rU^2(1{,}000,r)dr=2\pi 1.066\cdot 1.678^2\cdot\int_0^\infty r\exp\left(\frac{-r^2}{5304.5}\right)dr=$$

$$=18.86\frac{5304.5}{2}\cong 50{,}000\ N \text{ as expected.}$$

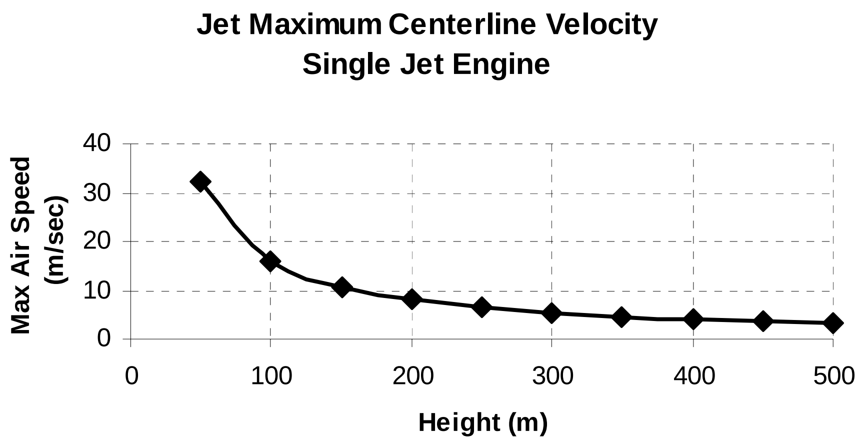

Figure A-2: Centerline maximum jet velocity. Initial speed 460 m s^{-1}.

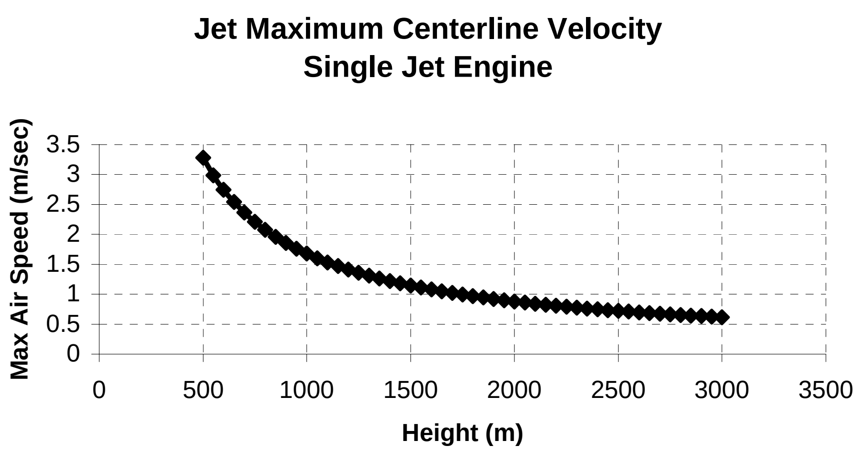

Figure A-3: Centerline maximum jet velocity. Initial speed 460 kg s^{-1}.

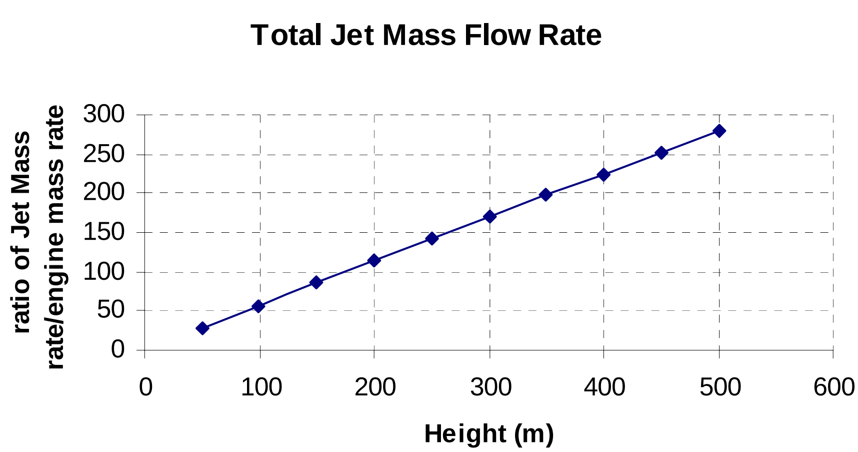

Figure A-4: Jet mass flow rate due to entrainment. Engine initial mass flow rate is 109 kg s^{-1} .

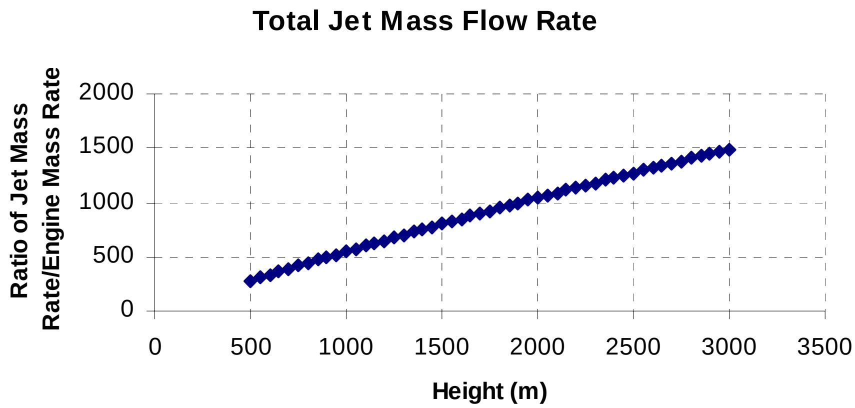

Figure A-5: Jet mass flow rate due to entrainment. Engine initial mass flow rate is 109 kg s^{-1} .

Planar Free jet

A planar jet has a rectangular cross section and an aspect ratio of at least 15:1. In a planar jet as in circular jet, the momentum flux is preserved. But in a planar jet the entrainment of air into the jet is slower than in a circular jer where the entrained air flows toward the jet radially. The result is that the jet speed for a planar jet is reducing with height slower than in a circular jet.

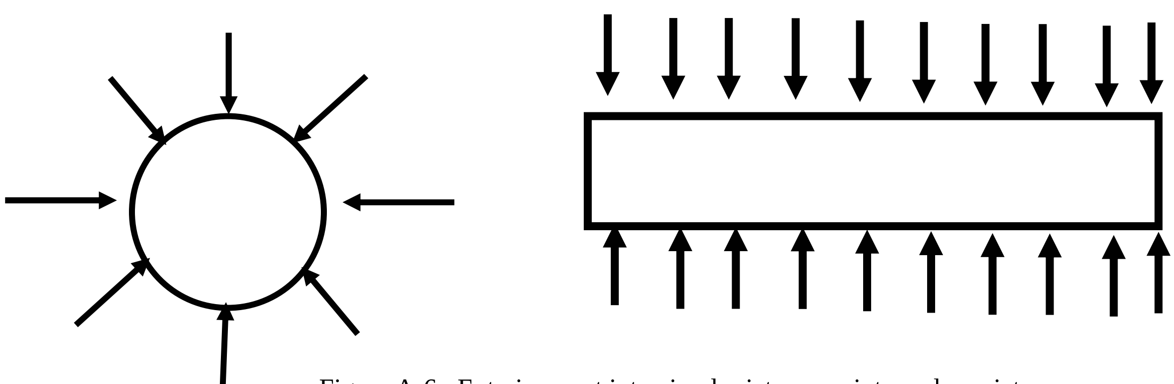

Figure A-6: Entrainnment into circular jet versus into a planar jet.

The equations governning the planar jet are:

$$\overline{U}_{mp}(x) = d_2 \cdot \frac{\sqrt{J'/\rho(x)}}{x^{0.5}} \tag{9}$$

In equation (9) J' is the momentum flux per unit lenth in [N m^{-1}], and d_2 is constant. The subnotation p is for "planar".

The velocity profile for a planar jet is:

$$U(x, y) = \overline{U}_{mp}(x) \cdot \exp\left(\frac{-y^2}{d_1^2 x^2}\right) \tag{10}$$

Where d_1 is a constant. d_1 and d_2 were found in the same manner as for circular jet to be (Rodi 1975):

$$d_1 d_2^2 = \sqrt{2/\pi} \qquad d_1 = 0.132 \qquad d_2 = 2.46 \tag{11}$$

For a planar jet the divergence of the jet is:

$$y_{0.5} = 011 \cdot x \tag{12}$$

Arrangement of Multiple Jet Engines

The application of many jet engines at one site for cloud formation may be necessary. The physical arrangement of the engines has three potential configurations.

In the first configuration the jet engines are far away from each other and each jet does not influence each other up to a certain height as defined by the cloud modeler. For that eq. (1) can be applied. This configuration is difficult logistically since each engine will require its own floating platform.

The second possibility is to use the engines in a circular cluster. In this case the cluster can be viewed as one large engine that provides momentum flux of N engines.

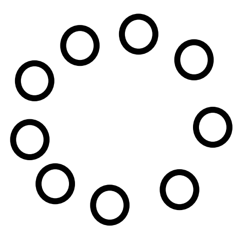

Figure A-7: Circular cluster of N jet engines

In this case:

$$\overline{U}_{mN}(x) = c_2 \cdot \frac{\sqrt{N \cdot J_{single} / \rho(x)}}{x} = c_2 \cdot \sqrt{N} \frac{\sqrt{J_{single} / \rho(x)}}{x} \tag{13}$$

It is possible to show that the air mass rate is also multiped by $\sqrt{N}$ in comparison to the mass flow rate of a single engine.

The third configuration is to have the N engines arranged in a straight row. In this case, the arrangement can be viewed as a planar jet where the momentum flux per unit depth is equal to the momentum flux of each engine divided by the distance L between the engines or:

$$J' = \frac{J_{single}}{L} \tag{14}$$

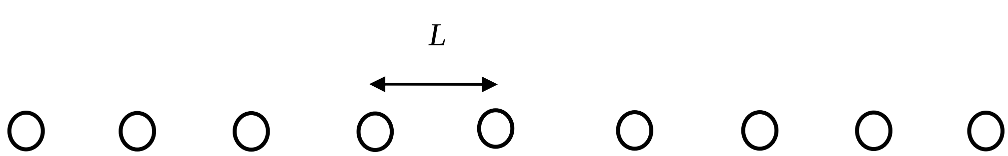

Figure 8: Planar configuration of N jet engines

Substituting (14) into (9):

$$\overline{U}_{mp}(x) = d_2 \cdot \frac{\sqrt{J_{single} / L \cdot \rho(x)}}{x^{0.5}} \tag{15}$$

The essential difference between a circular and a planar jet arrangement is the dependency of of the jet maximum velocity on the height. In the planar case the speed is proportional to $1/x^{0.5}$ while for a circular arrangement it is proportional to $\sqrt{N}/X$. In the planar case although the velocity of the jet may be higher (for a certain L), the total mass flow may be lower.

These calculations enable the cloud modeller to conduct optimization analysis for the best arrangement at various times during operation. If multiple floating platforms are used, it might be that at a certain time it will be better to use one configration while at a another time another configuration.

Summary

This outline provides a discussion of the mechanics of a compressible free jet produced by a single and multiple jet engines. It is important to note that the initial momentum of the jet is preserved under any atmospheric condition regardless of atmospheric stability.

The fundamental question concerning cloud formation is if the free jet will produce plumes and updafts of substantial proportions to cause or accelerate formation of a substantial cloud system. The jet is formed due to pressure difference in the nozzle of the jet engine, while plumes are generated by kinetic and then bouyant forces. The air mass flow rate generated by the jet engines is not enough to create a substantial cloud system, but perhaps to trigger its formation. Further investigation is required to determine the effects of condensation and on the necessary profile of the potential temperature in the atmosphere that may foster cloud formation.

Logistical considerations such as the availability of jet engines, load on the floating platform due to downward thrust, fuel weight, fuel cosumption, and corrosion impact on the engines will be covered in subsequent studies.

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1. Rodi, W., in *Studies in Convection*, P. 79-165; Launder, B.E., Editor, Academic Press, London, 1975.

2. Abramovich, G.N., *The Theory of Turbulent Jets*, The MIT Press, 1963.