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EXPLORING IN AEROSPACE ROCKETRY

8. ZERO-GRAVITY EFFECTS

by William J. Masica
Lewis Research Center
Cleveland, Ohio

Presented to Lewis Aerospace Explorers
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1966-67

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Gravity is as familiar to us as breathing and probably just as much taken for granted. We expect water to be at the bottom of a glass, warm air to rise, a football pass to be completed, and, when we sit, to have a certain part of ourselves in firm contact with an object on the ground. We view balls that roll uphill and Indian rope tricks with suspicion, for experience tells us that we cannot defy gravity.

Isaac Newton, at the early age of 23, was the first to really define the operations of gravity. Using the idea of accelerated motion discovered by Galileo and the planetary data supplied by Brahe and Kepler, Sir Isaac, with brilliant insight, arrived at the universal rule of gravity:

> The gravitational force or the force of attraction between two bodies is directly proportional to the product of the masses of the two bodies and inversely proportional to the square of the distance between them.

Expressed mathematically,

$$F = G\frac{m_1 m_2}{r^2}$$

where G is a constant. To be precise, this equation applies only to very, very small volumes of mass. Given a little more time (needed to develop calculus!), Newton was able to show that his equation also applied to any spherical mass of constant density material. The gravity force acts as if all the mass were at the center of the sphere, and the r in the equation is the distance between the centers of the spheres.

The amazing part about this rule is that it is universal. Provided that we do not ask too many questions, Newton's equation works 99.44 percent of the time. The gravitational force between masses of any shape can be calculated by breaking a large body into many small mass volumes, using Newton's equation to find the force caused by each of these small masses, and then adding all the forces together. Only the arithmetic becomes more difficult.

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Newton's gravity equation is an experimental rule; that is, it describes most observed facts of gravity. It cannot be derived, and it avoids explaining why or how one mass body attracts another. Einstein pretty well completed the remaining 0.56 percent of the problem when he developed his theory of general relativity. Despite numerous challenges, general relativity has remained virtually unchanged since its formulation over 40 years ago - a truly remarkable fact (and testimonial) in view of the sweeping changes in every other area of science. Today, Einstein's theory of gravity is generally accepted because it appears to agree with experimental observations. There remains, however, considerable disagreement as to just how good is the agreement. Recent measurements of the shape of the Sun by Dr. R. H. Dicke and his colleagues at Princeton University seem to suggest that Einstein's theory needs some modification. Professor Dicke's challenge is being taken seriously. The debates continue in the scientific periodicals, and apparently it will be some time before the question is resolved. (For a readable text on gravity, including some of the original relativistic aspects, see ref. 1.)

ZERO GRAVITY

What would a world without gravity be like? In a classical world (one with reasonably large objects, times of the order of minutes and hours, and speeds well below the speed of light - in brief, the kind of world we live in), Newton's gravity equation works very well. According to Newton's equation, a gravity-free world would then be effectively a massless world. For example, if the only mass system in our world were a glass of water, the glass of water would experience no gravitational force. But, the mass of the water alone would still cause some small gravity force on the glass. The gravity forces due to the mass of water in a glass are extremely small, so small that they can be regarded as zero, simply because the masses themselves are small. For all practical cases, then, a gravity-free world could mean a world of small mass volumes, where very massive objects, such as planets, are absent. Actually this is only one way of picturing a gravity-free world. If the glass of water could be magically placed at a spot between the Earth and the Moon where the gravity caused by the mass of the Earth exactly cancels the Moon's gravity, the glass of water is in a gravity-free environment. The gravity force caused by the other planets is negligible because of their remoteness.

A third way of describing a gravity-free world is a very practical one that can actually be obtained. Imagine that you are on an elevator, initially resting at the top floor. In one hand you are holding a ball, in the other, a glass of water. You feel gravity acting on your body because the elevator floor is in contact with your feet, pushing up with a force exactly equal to your weight. If you drop the ball, it falls, accelerating at a rate of about 32 feet per second per second. Just as you pick the ball up, the elevator cables break, and the elevator begins to fall. Because of a streamlined elevator floor, there is no air drag, and you and the elevator begin to accelerate freely. While pondering your fate, you notice that the familiar tug of gravity on your body has vanished - to oversimplify, your feet cannot quite catch up to the elevator floor. If you gently release the ball, it will just stay there, floating in the elevator. As far as you are concerned, your short-lived world is gravity-free. Of course, the panic-stricken fellow standing on the ground sees all sorts of gravity forces: you, the elevator, and the ball all accelerating downward because of the Earth's gravity force.

A gravity-free world, or zero gravity, or weightlessness is, therefore, a relative thing. In general, zero gravity means more than the effective absence of gravitational force in a world of small masses or at certain select places in space between planets. As long as a body, a rocket ship, or a glass of water is accelerating freely under gravity-type forces only, with no friction, air drag, or other forces acting, it will be in a zero-gravity environment to an observer moving along with it. Thus, the contents of a rocket with its engine shut off, coasting freely towards the Moon, are in zero-g. Objects on a platform falling freely on Earth in a vertical tower, evacuated to eliminate air drag, are in zero-g. The contents of a Gemini capsule that is moving freely in a stable orbit around the Earth are in zero-g. (Contrary to some popular statements, the net force acting on an orbiting spacecraft is not zero, nor could it possibly be zero - remember Newton's first law of motion?) Since friction-type forces are almost always present, a practical definition of zero-g, preferably in mathematical form, is still required. Later in this chapter, such a definition of zero-g for a fluid system is given.

Your quick thinking has saved you in that ill-fated elevator ride. While calmly awaiting rescue from the crushed elevator, your thoughts return to what happened during your brief moments in zero-g to the water in that glass you are still holding.

SPACE FLIGHT IN ZERO GRAVITY

The requirements of space flight have stimulated zero-g research. How will man, his life-support equipment, space vehicles, and all the various systems used in space flight perform in zero-g? The problems, which are many, range from the subtle biophysical ones to the very practical problem of just turning a wrench. Since systems such as liquid propellants and life support are vital, much attention has been given to finding out what happens to a liquid-vapor or fluid system in zero gravity. A few of the problems and questions which have to be answered are shown in figure 8-1. This figure shows a

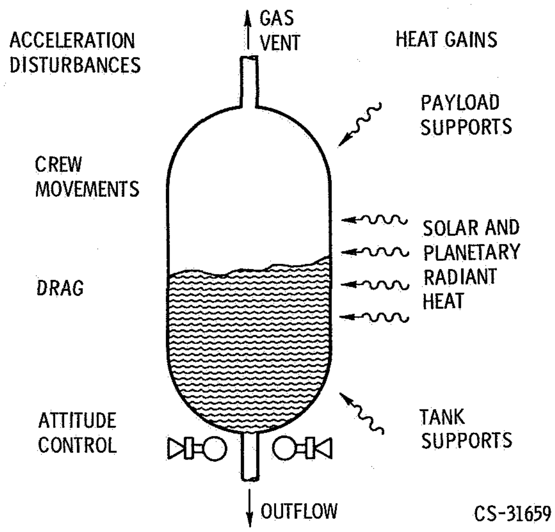


Figure 8-1. - Fluid management problems.

propellant tank holding a cryogenic fluid (liquid hydrogen, liquid oxygen, etc.). On Earth under normal gravity, or 1-g conditions, the liquid is exactly where it should be: like water in a glass, the liquid is at the bottom. If liquid must be removed to start our engines on the pad, all that is needed is an outlet located somewhere at the bottom of the tank. Since cryogenics evaporate very easily and build up pressure in the tank, a vent located at the top of the tank can be opened to prevent a pressure explosion. If the vent is opened while the rocket is on the ground or during launch, only gas or vapor will be lost and not the precious liquid fuel supply.

In zero-g while the vehicle is coasting, the requirements are much the same. The liquid should be at the tank outlet in order to be able to restart the engines; because of the heat from the Sun and the like, the tank must be vented. Consequently, the liquid and vapor must be in a proper position in the tank. The problems have, however, been increased in zero-g. Now an attitude control maneuver, for example, could easily cause the liquid and vapor to move around in the tank. In zero-g, the liquid will not necessarily return to the bottom or pump outlet part of the tank as it would in 1-g; gone is the reliable restoring force of gravity.

CAPILLARITY AND SURFACE ENERGY

The first question is obviously what is the shape of the liquid surface in zero-g? The glass of water in 1-g has a fairly flat liquid surface or (to sound scientific) liquid-vapor interface, except near the walls of the glass, where the liquid curves up slightly. This curvature near the walls is due to very short-range, molecular forces that act something like electric forces. Another force, which acts along the entire liquid surface, is the surface tension force. Usually, we forget all about these forces in 1-g because they are very small; but in zero-g these are the only forces present and, therefore, these capillary forces are, relatively speaking, very large.

Surface tension, or the fact that a liquid surface acts like a thin elastic film, is not quite a force. It might act like a force, but surface tension is really an energy-type quantity. Energy is a defined quantity used in physics and is very handy and easy to work with; it is a scalar, that is, a number. Numbers can easily be added, multiplied, or otherwise handled. A force is a vector and not quite so simple to work with. For example, as in chapter 9, if you want to add forces, you must consider both the magnitude and the direction of each force. In one form, energy is the amount of work or effort required to move something somewhere. An arbitrary numbering system is given to energy to indicate that it takes more work to push a car 50 feet than to push it 5 feet. Closely related to the definition of energy is the principle that all physical systems, when left alone, take the path (or shape or form) that requires the least amount of energy. Although this is given without proof, the principle is very familiar to all of us: we do the least amount of work to get a job done. Nature happens to work the same way.

The idea of energy and the principle of minimum energy are powerful tools in physics. Together they can be used to solve many problems. They are especially useful in capillarity. It takes work to remove a molecule from a liquid or solid surface; the larger the area between the molecule and its neighbors, the easier it is to pull out that molecule. For liquids, this amount of work, or energy, divided by the available area is called the surface tension. Generally, a large group of molecules over any unit area (an area of 1 mm^2, 1 cm^2, etc.) is usually considered. Surface tension is then an energy per unit area. Solids also have surface energies, and, as one might suspect, these are usually larger than those of liquids. It takes more work to pull out a tightly held metal surface molecule than a rather loosely held liquid surface molecule. Most liquids have surface energies in the range from 2 to 80 energy units per unit area, while solids cover the wider range from about 15 to over 800 energy units per unit area.

Surface energy and the principle of minimum energy explain many everyday facts of capillarity. Water has a surface tension of 70 energy units per unit area. Wax has a surface energy of about 40 energy units per unit area. Water on a newly waxed car beads because the solid wax surface has the lower energy. The water tries to cover as small an area of the lower energy wax surface as possible. This is the same principle behind the nonstick frying pans. These solid surfaces have very low energies, much lower than most food products. Thus, by the minimum energy principle, food will not stick to form new surfaces of higher energy. Of course, things also happen in reverse - a drop of oil with a surface tension of 30 will spread on wax to try to keep the new surface energy at a minimum. Detergents, another example, lower the surface tension of water and, among other things, let the water spread more easily over fabrics to aid in washing.

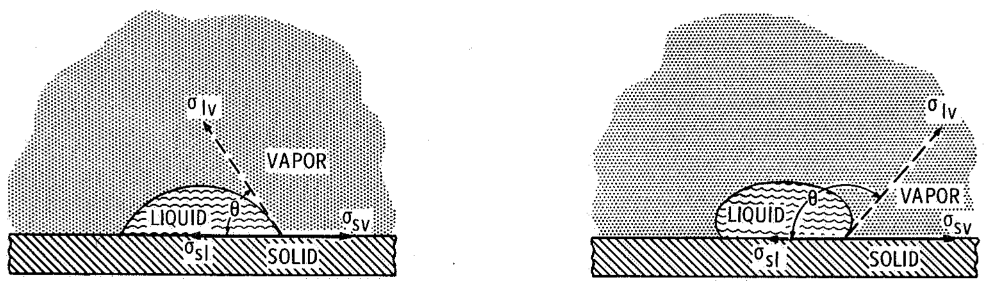
It is essential when using minimum-energy principles that all the energies be considered. In the last paragraph, we have quite incorrectly neglected one of the energies. All solid-liquid-vapor systems (a glass of water, for example) have three surface energies: the liquid-to-vapor, the solid-to-vapor, and the solid-to-liquid surface energies. If gravity is present, there is also the gravitational energy, for it takes extra work to move something against the gravity force. When each surface energy per unit area is multiplied by the area that particular surface covers, the product is an energy term, or simply a number. For example, if σ_{lv} represents the surface energy per unit area of the liquid-vapor surface and A_{lv} is the area of that surface, then

$$\sigma_{lv} \times A_{lv} = \frac{\text{Energy}}{\text{Area}} \times \text{Area} = \text{Energy}$$

All the energy terms are added to give the total energy, and according to the principle of minimum energy, this total energy will be as small as possible. The only way the energy can change is if the areas of the surfaces change. Since all the areas cannot be made as small as possible (the glass of water is a fixed size), those that multiply the largest surface energies will be changed more. Thus, the liquid shape will be that shape where the surface areas become as small as possible, with the largest area changes being for those terms that affect the energy the most.

CONTACT ANGLE

Finally, the boundary conditions have to be considered. One obvious boundary condition is that the liquid is in the glass; another condition is the contact angle. For many combinations of liquids and solids, the spreading of the liquid is not perfect. The liquid meets the solid at some definite angle. This angle is called the contact angle (θ in fig. 8-2) and its value may range from 0° to well above 90°. Water on a very clean glass surface has a 0° contact angle; on wax, about 90°. Mercury on glass has about a 130° contact angle. Obviously, the contact angle is related to the surface energies. For example, a high contact angle means that the surface tension of the liquid is probably greater than the solid surface energy. The contact angle has been shown both theoretically and experimentally to be independent of gravity. Its value remains constant whether at 1-g or zero-g.

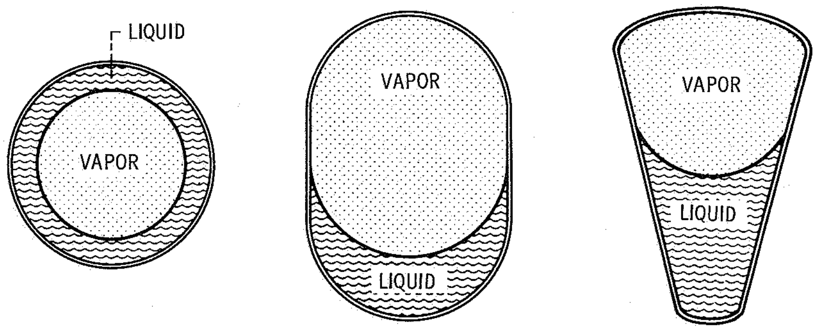


(a) Wetting liquid, 0° < θ < 90°. (b) Nonwetting liquid, 90° < θ < 180°.

Figure 8-2. - Contact angle definition.

LIQUID SURFACES IN ZERO GRAVITY

With this information we can now explain what happened in that glass of water during the elevator ride. In zero-g the only forces present are capillary forces. According to the principle of minimum energy, the zero-g shape will be that shape where the sum of the surface energies is the smallest. This sum is made small by changing the areas of the liquid, vapor, and solid surface, while keeping the contact angle the same. Figure 8-3 shows the zero-g shapes in various tanks for liquids with a 0^{o} contact angle. The zero-g interface shape in a spherical tank is a vapor bubble, completely surrounded by liquid. In a partly filled cylindrical tank the liquid forms a hemispherical surface. Notice that in each case, the area of solid (to vapor) is "minimized" to keep that relatively



(a) Spherical tank. (b) Cylindrical tank. (c) Conical tank.

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Figure 8-3. - Zero-g interface configurations for 0° contact angle liquids.

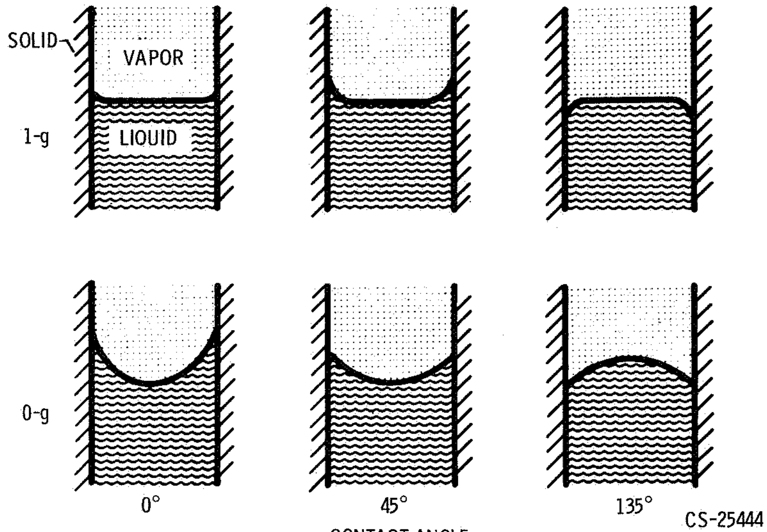
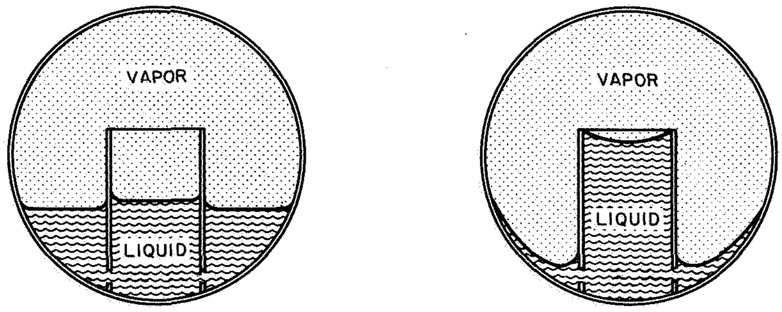


Figure 8-4. - One-g and zero-g interface configurations.

large energy term as small as possible. Figure 8-4 compares surface shapes in a cylinder for different values of contact angle. In summary, the zero-g interface shape depends on three things: the fluid properties including the contact angle, the shape of the container, and the percentage of liquid in the tank. Given these, the zero-g shape can be defined by use of the idea of minimum total energy.

ZERO-GRAVITY BAFFLES

It is apparent from figure 8-3 that the zero-g location of the liquid and vapor could cause problems in rocket engine restart and venting operations. In a spherical tank, for example, the vent may be covered by liquid. Some method of positioning the liquid in zero-g is necessary. Since liquid surface shape in zero-g depends on tank shape, the position of the liquid can be controlled by changing the interior shape of the tank, for example, by adding baffles. A simple baffle is shown in figure 8-5. It is merely a tube mounted over the tank outlet with holes provided to allow the liquid to flow freely between the tank and the tube. For this baffled tank, a 0^{o} contact angle liquid fills the tube over the tank outlet while the remaining liquid is distributed around the tube. Note that the tube also positions the vapor at the vent part of the tank. Another type of baffle is shown in figure 8-6. It consists of a sphere mounted off-center in the direction of the tank outlet within the main spherical tank. It can be shown, to use the familiar textbook words (which usually means, as it does here, with a lot of work), that these zero-g shapes do result in minimum total surface energy.



(a) One-g configuration.

(b) Zero-g configuration.

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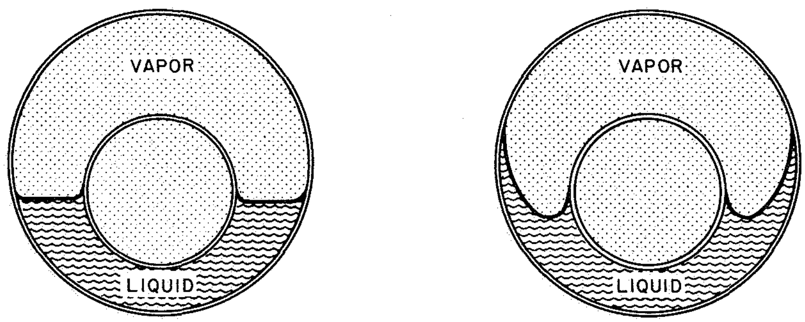
Figure 8-5. - Capillary standpipe baffle.



(a) One-g configuration.

(b) Zero-g configuration.

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Figure 8-6. - Spherical baffle.

Baffles like these work fine in zero-g, where surface energies are dominant, but they usually cannot position the liquid under conditions of acceleration disturbances, such as those from space vehicle attitude control or docking maneuvers. However, they are able to move the liquid back to the desired location once the disturbance is removed. Figure 8-7 shows a baffled tank with the liquid away from the desired position, as if displaced by some acceleration. Once the disturbance is removed, and a zero-g condition is restored, the liquid will return to the desired position over the tank outlet. All that is needed is that the liquid initially reach the baffle, so that it "knows" its minimum-energy shape.

There are many other kinds of baffles, as well as other methods (a piston, spinning the tank, screens, use of electric forces acting on the liquids, and acoustics are just a few) which can be used to control liquid in zero-g. All have their advantages and disadvantages (weight, sizes, reliability, etc.). One major advantage of passive baffles is that they have no moving parts, but one big disadvantage is that they generally cannot

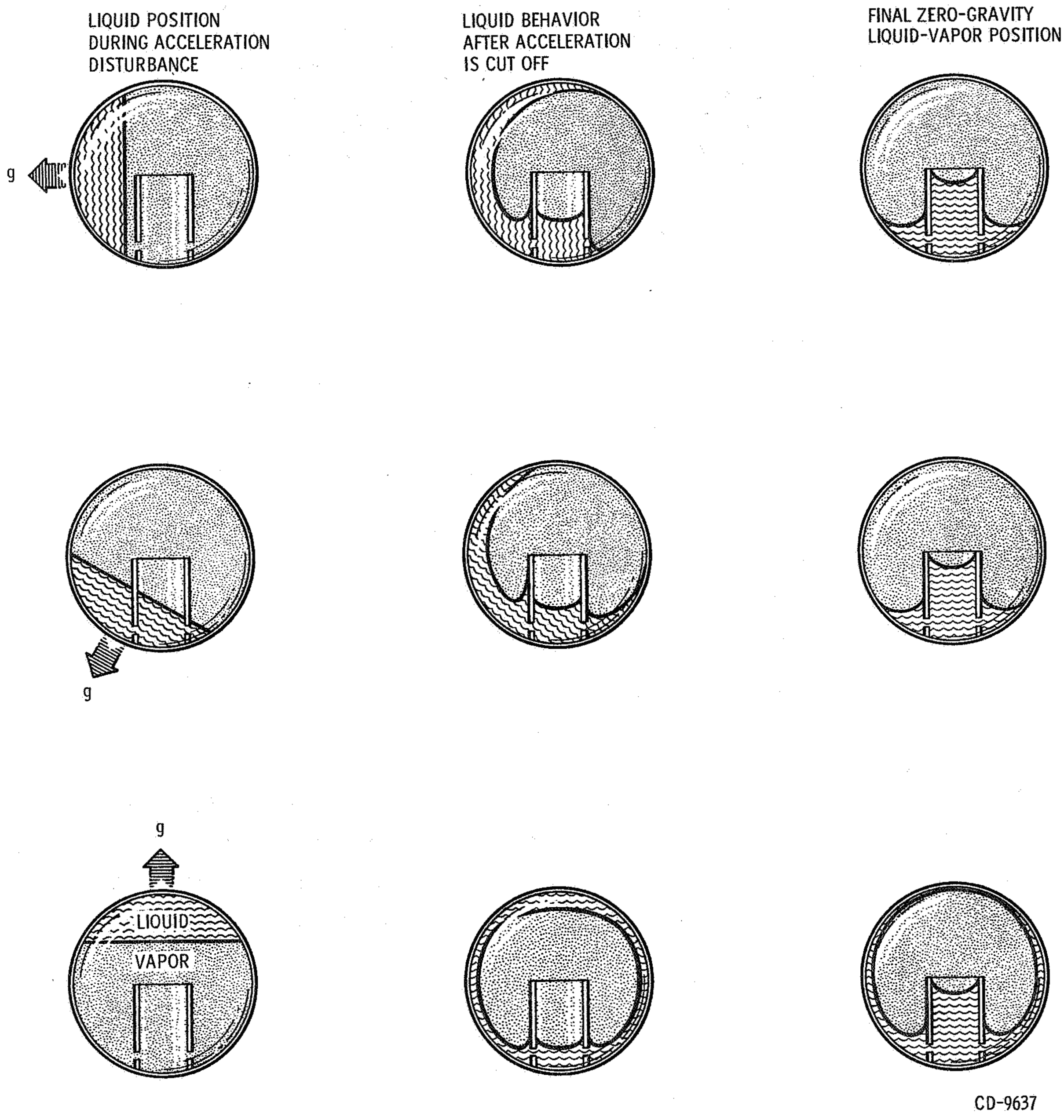

Figure 8-7. - Fluid behavior in baffled tanks.

guarantee that the vapor will be at the vent, especially under very low-g rather than zero-g conditions.

BOND NUMBER

At this stage in the discussion, it is very disheartening to admit that true zero-g does not exist. The streamlined elevator floor of the earlier example will produce some drag because the elevator shaft cannot be evacuated completely. Even a rocket ship in space will have solar wind and light pressure causing small but measurable forces. In brief, "accelerating freely" is really impossible. When the Agena-Centaur or Saturn coast in low Earth orbits, they all will be in a low-g field as a result of atmospheric drag. Although the effective accelerations due to the air drag at these altitudes may be small, say less than 0.00001-g (10^{-5}-g), they are significant.

A quantity called the Bond number indicates how large the acceleration forces are in comparison with the capillary forces. For a cylinder, the Bond number is

$$Bo = \frac{aR^2 \Delta\rho}{\sigma_{lv}}$$

where a is the effective acceleration, R is the cylinder radius, $\Delta\rho$ is the difference in density of liquid and vapor, and σ_{lv} is the surface tension. The Bond number appears in all mathematical solutions of low-g fluid problems. For our purposes, the Bond number may be regarded as an experimentally defined quantity. The Bond number has no dimensions. For Bond numbers much less than 1, surface tension is dominant; for Bond numbers greater than 1, gravity dominates. A glass of water in 1-g has a Bond number of about 200 - gravity is important. For liquids, zero-g really means that the Bond number of about 200 - gravity is important. For liquid, zero-g really means that the Bond number is very small, say less than 0.01. In a fluid system, gravity or acceleration-type forces can be neglected below Bond numbers of 0.01.

If a cylinder is small enough, the Bond number will be small, even in normal gravity conditions. The liquid surface in a soda straw looks like the zero-g shape in figure 8-4, even though the straw is not accelerating freely, but is motionless in 1-g. This is so because zero-g is a relative thing and to a fluid system of small size, gravity effects may be very small when compared with others. On the other hand, in a tank of large radius, a very small acceleration could result in a significant gravity effect. In general, a large Bond number (greater than about 100) means a flat liquid surface and that gravity or acceleration effects are important. A low Bond number (say less than 10) means that capillary effects predominate and, if the contact angle is small, a highly curved liquid

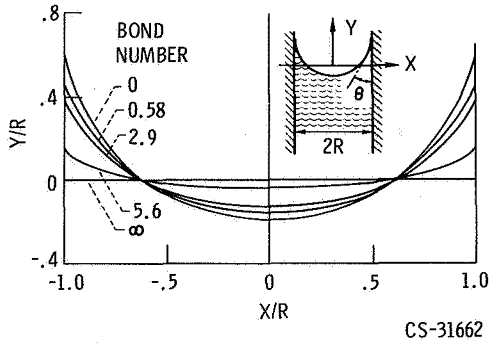

Figure 8-8. - Calculated interface configurations at various Bond numbers when $\theta = 10°$.

surface results. A set of interface shapes for different Bond numbers is shown in figure 8-8.

In the real case of low Earth orbits, the Bond number is particularly useful. Air drag will act in a direction to cause the liquid to move. A liquid surface is not capable of resisting very much acceleration before it starts to move. For instance, although water will run out of an inverted glass, it will remain in the straw as long as the top end stays closed. How large an acceleration can be applied (or, in 1-g, how large can the straw's radius be) before liquid will move? Surface tension prevents the liquid from flowing in a straw, and the overall criterion of liquid flow is given by the Bond number. If the Bond number is less than about 1, no liquid will flow; if the Bond number is greater than 1, liquid will flow. Some of the data which provided this information are shown in figure 8-9.

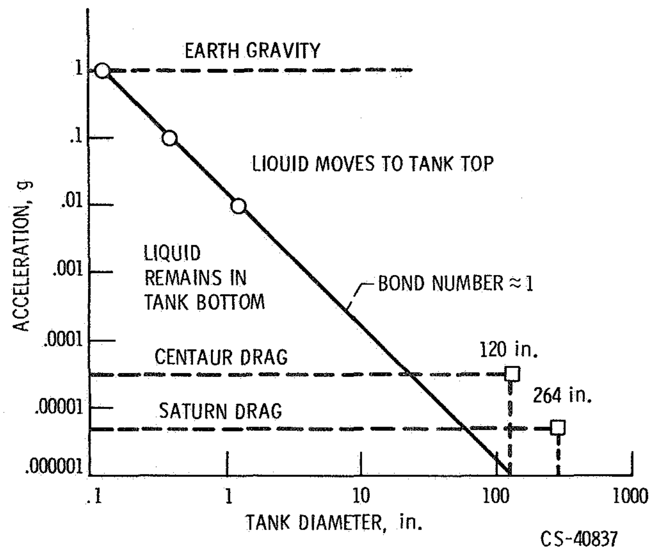

Figure 8-9. - Criterion for liquid stability.

For vehicles like Centaur in low Earth orbits, the Bond number is greater than 1 because of the large radius of the vehicle's tank. Thus, under the action of very small drag forces alone, the liquid propellants will move to the front of the tank. While baffles could trap some liquid at the pump inlet of the tanks, no baffle of reasonable weight can positively prevent liquid from covering the vent. For Centaur and Saturn, a positive method of locating the propellant was required. The chosen systems are similar and are summarized in figure 8-10. Each system positions the propellants during the entire coast period by applying a small acceleration sufficient to overcome the drag. The Bond numbers created by the accelerations are greater than the Bond number caused by drag. In the case of Centaur, this acceleration is produced by small rocket engines which burn for the entire 25-minute coast period. The Saturn system obtains thrust by properly directing the vented gas from propellant boiloff.

Residual air drag and its effect on propellant location is only one of the many problems. When the vehicle shuts off its engines to enter the coast period, other types of disturbances act on the propellant. The tank walls may give a little and then spring back, propellant slosh or the back-and-forth movement of the liquid in the tank may build up, and various return lines leading from the engine pumps to the tank may create liquid streams into the tank. If nothing were done to prevent these disturbances, the propellant would indeed be in a chaotic state. Eventually, the propellant would settle, but venting might be required in the meantime. A large part of zero-g development goes into finding simple and reliable ways of preventing or damping out liquid disturbances. The settling thrusts are increased in size to handle large liquid flow velocities, and various baffles are used to keep propellant sloshing below some reasonable level.

For long-duration space missions, the continuous application of even a small thrust

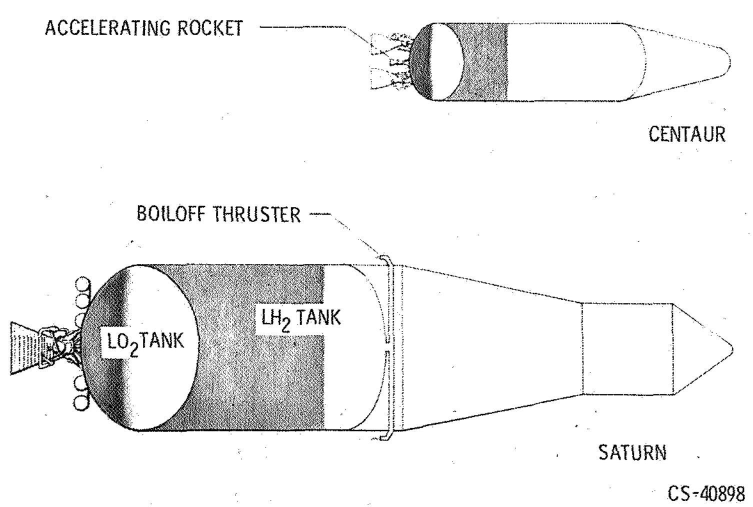

Figure 8-10. - Cryogenic propellant management systems.

to maintain liquid-vapor control would result in an important weight penalty. The subject of heat transfer - how the heat inputs build up the tank pressure - requires additional study. Heat transfer depends in part on free convection (for example, warm air rising) and buoyancy effects (an air bubble rising in a liquid to the surface). Both of these rely on density differences and gravity, and, therefore, free convection and buoyancy are reduced or entirely absent in zero-g.

A large part of the research investigating these and other similar zero-g problems is conducted at the Lewis Research Center. Lewis has two drop-tower facilities to produce short-time-duration, zero-g and low-g environments. The drop tower is identical to the freely falling elevator. One tower uses a drag shield around the experiment to reduce air

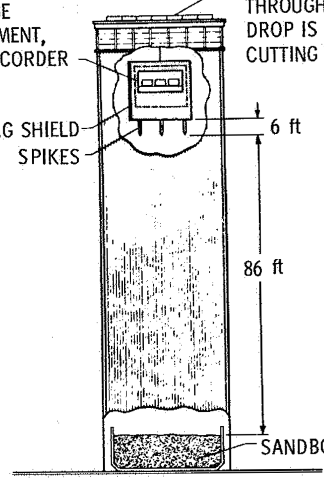

Figure 8-11. - Drop tower zero-gravity facility. Maximum payload, 500 pounds; 2.25 seconds of gravity less than 10^{-5}-g.

drag (fig. 8-11), while the newest zero-g facility (fig. 8-12) uses an evacuated chamber. In both facilities, the drag acceleration is less than 10^{-5}-g, so that if our experiments are reasonably sized, very low Bond numbers (or zero-g) can be obtained. Zero-g times range from about 2 to 10 seconds. To obtain the 10 seconds, the experiment is shot upwards by an accelerator or cannon-like piston. As soon as the experiment leaves the accelerator, it is moving freely under the influence of gravity only. Both the up and the down flight of the experiment will result in a zero-g condition. While 10 seconds does not seem to be a long time, and it is not, things happen relatively faster in small model tanks. Drop-tower results can be scaled up to larger sizes and longer times by using scaling-type parameters (numbers) like the Bond number.

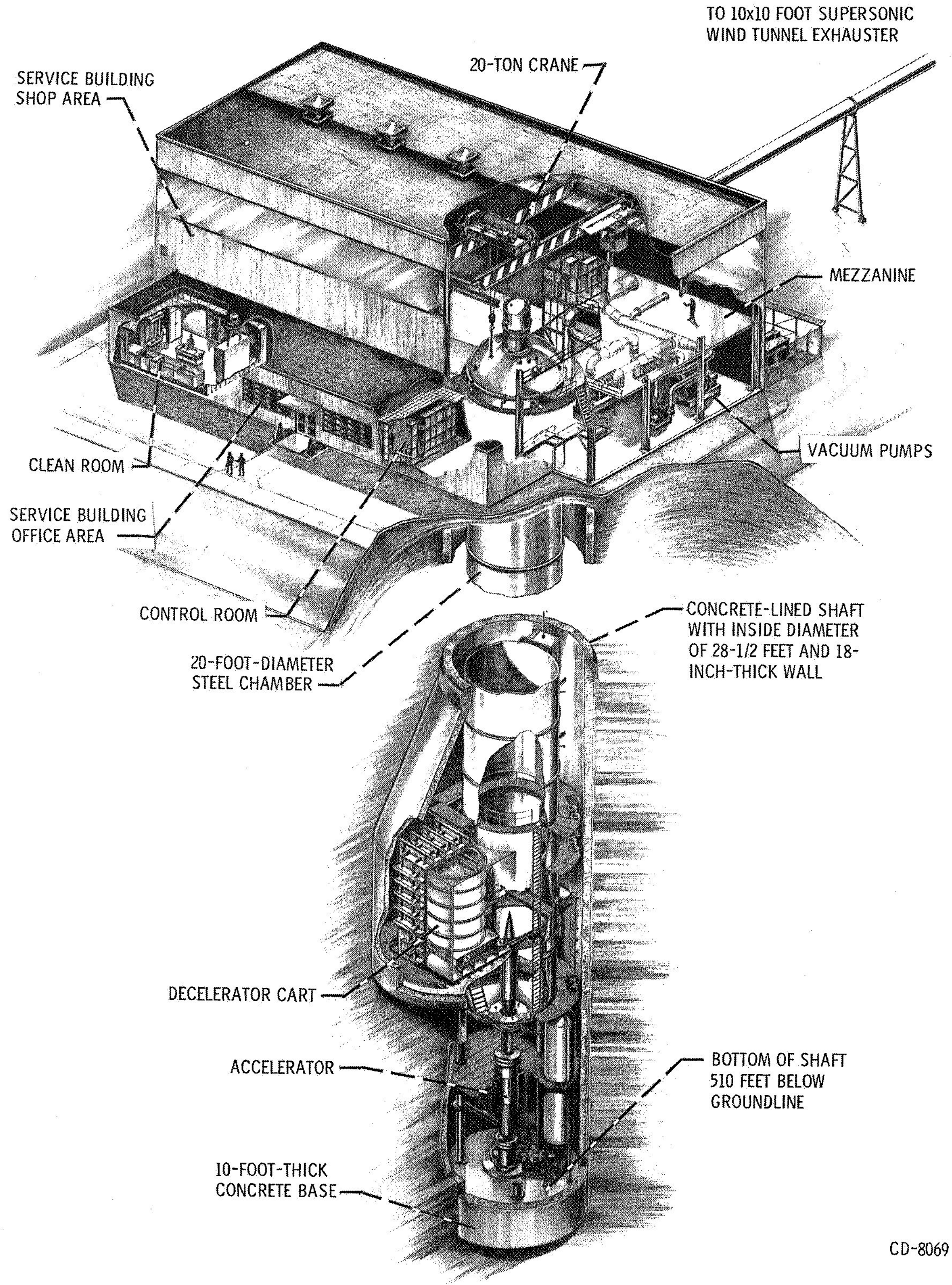

Figure 8-12. - Cutaway view of 10-second zero-gravity research facility.

In conclusion, we have examined the meanings of zero gravity, the importance of capillarity and surface energy, the powerful physical tools of energy and the principle of minimum energy, and the behavior of fluids in zero-g. The subject is fascinating, covering the full range from the implications of relativity to the practical areas of manned space flight in a world free of gravity.

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