A Survey of Large Propellant Tank Quantity Gaging Methods in Zero-G

Clyde Wiley
Engineer/Scientist, McDonnell Douglas Astronautics Company-West
A SURVEY OF LARGE PROPELLANT TANK QUANTITY GAGING METHODS IN ZERO-G

Clyde Wiley
Engineer/Scientist
McDonnell Douglas Astronautics Company-West
Huntington Beach, California

ABSTRACT

This zero-g gaging survey excludes methods used with tanks small enough for positive expulsion. Gaging prototypes have been developed, but no satisfactory method was devised that could meet the Apollo/Saturn design deadline. Advanced space systems designs, such as the Space Shuttle, have generated a new interest in zero-g gaging. The operating principles of developed concepts are analyzed for application to cryogens and kerosenes and for accuracy comparison to conventional gaging. Actual need for zero-g gaging is also analyzed for design compromises to allow a realistic choice from concepts that have yet to be tested in a zero-g environment.

INTRODUCTION

The zero-g gaging survey was conducted as a result of a Space Shuttle Propellant Utilization and Propellant Gaging Trade-off Study. The intent of the gaging study was to survey the current state-of-the-art for advanced design application. This study indicated that large cryogenic tank gaging in zero-g may become a requirement for the Space Shuttle orbiter stage auxiliary tanks. A survey of the zero-g quantity gaging state-of-the-art revealed that candidates for large cryogenic propellant tanks have never gone beyond the prototype stage, have never been tested in a true zero-g environment, and some have not been tested with cryogens.

All contractual progress reports reviewed state that achieving 0.5 percent accuracy is “theoretically possible” and to obtain a more objective view, the operating principles of four zero-g concepts are studied and their application to cryogenic propellants are considered. In the author’s opinion, a more pragmatic analysis indicates that zero-g gaging will not achieve the accuracy of conventional gaging within the next decade. For this reason, the actual need and acceptable accuracy of zero-g gaging is analyzed.

OPERATING PRINCIPLES AND CURRENT TEST RESULTS

Total Tank Capacitance

A capacitance approach to the problem of gaging propellant tanks in a zero-g environment was investigated by Trans-Sonics, Inc. under a NASA/MSFC contract. The technique involved surface electrodes attached to the inside tank wall so that the whole tank became the inside of a capacitor. The test results are quoted from Section 5.5 of Reference 1:

“1. The change in capacitance when the model tank was partly filled with liquid was only about half the expected value.

2. The nonlinearity of capacitance change with liquid volume was much greater than anticipated.”

The report stated that a review of the problems indicated the capacitance concept was correct but the particular design was wrong. Unfortunately, the contract was terminated and data from a new design has not supported this theoretical analysis.

Nucleonic Gaging

Nucleonic techniques utilize a radioactive source and a radiation detector; these can be used completely external to the tank when x-ray or gamma ray radiation is used. The α and β particles are used for fluid density measurement and not mass measurement due to their short penetration capability (a few inches in gas for α and in liquid for β).

X-rays are penetrating electromagnetic radiation having wave lengths shorter than the high energy portion of ultraviolet light. This broad spectrum includes gamma rays, but more common usage implies the source is nonnuclear and is the only description of the spectrum between ultraviolet and gamma rays. Photon energy is inversely proportional to wavelength, and gamma rays are high energy photons ranging from below 10⁴ electron volts (10 kev) to over 10⁷ electron volts (10 mev). X-rays will be considered in the common usage as lower energy photons in the 0.1 kev to 10 kev range.

The basis of nucleonic gaging lies in the interaction of emissions from radioactive sources with matter. These sources are currently being used because they are plentiful, cheap, lightweight, and very reliable. The use of x-ray tubes has the advantage of being able to activate only when necessary, but the disadvantages of weight, power requirements, and tube lifetime have, to the present, outweighed any advantages. However, a recently patented hybrid device will be discussed in the following paragraphs.
There are three significant basic interactions but only two are relevant to nucleonic gaging. These are photoelectric absorption (low energy, \(E < 0.05 \text{ mev}\)), and Compton scattering (0.05 mev \(< E < 1.02 \text{ mev}\)). When low energy sources are used, with the photoelectric effect in the dominant probability, the incident photons are completely absorbed in the atom. The interaction results in recoil of the entire atom (thermal energy) and the release of a photoelectron in the infrared spectrum. Therefore, the interacting photons will not be observed by a detector and a linear attenuation (on a semilog scale) equation may be used:

\[
\frac{I}{I_0} = e^{-\mu m x}\rho
\]

where,

- \(I\) = intensity of radiation detected (disintegrations per second per unit area)
- \(I_0\) = source intensity
- \(\mu m\) = mass absorption coefficient (cm\(^2\)/gm)
- \(x\) = thickness of absorber in cm
- \(\rho\) = density in gm/cm\(^3\)

If Compton scattering is involved, the Compton scattered photons also are detected. In this case, the attenuation equation is:

\[
\frac{I}{I_0} = B e^{-\mu m x}\rho
\]

where,

- \(B\) = buildup factor due to the Compton scattered component

The Compton scattered component has two characteristics which differentiate it from the incident photon (1) lower energy and (2) different direction. The most common way to reduce the effect of the scattered component is to collimate the source and detector. Another approach is to utilize a detector with high photon energy resolution which can discriminate between various energy levels and thus ignore the lower energy scattered component. The latter is a difficult goal to achieve for Compton scattering, but detectors with high energy resolution have other advantages, such as limiting backscatter effects.

There are two basically different methods for mechanizing nucleonic propellant gaging. (2) They are classified as exponential and linear. The exponential system uses collimated source-detector pairs; it measures the tank in small columns and then sums the contribution of all columns. This method requires a set of electronics in each detector, but it has the advantage of accommodating large tanks of high density propellant. The linear system uses high resolution detectors with the source-detector combinations not collimated. A group of detectors, usually about six, can be operated in parallel and use common electronics. This method has the disadvantage of requiring low density fluid or small tanks. Reference 2 contains excellent details of zero-g nucleonic propellant gaging concepts. This proposal was authored by Mr. Kim A. Kaminskas, one of the pioneers in zero-g nucleonic gaging, and the proposal resulted in TRW Systems Group winning the design competition for a USAF nucleonic gaging zero-g study contract.

Radiation intensity and crosstalk are the two most controversial aspects of nucleonic gaging. Actual test results by Giannini Controls Corp. (now Conrac Corp.) at a NASA/MSFC, Huntsville, large LH\(_2\) tank slosh facility (5/8-scale S-IVB tank) indicated that radiation safety was not a problem. (3) Maximum radiation intensity inside the tank was 2.5 mr/hr with a 0.1 mr/hr dose rate at normal working positions. However, large LOX tanks could present a problem due to the high density of LOX. Crosstalk is a term used to describe unwanted radiation from other sources or backscatter. The use of collimated sources, high discrimination detectors, and low energy photons can reduce many of these problems. Recent advances in sources and detectors may solve many of these problems.

A hybrid source/x-ray device that is in the early stage of development by TRW Systems Group(4) is shown in Figure 1. The device uses a beta emitting source to replace the heated cathode of an x-ray tube. X-ray production results from a process called Bremsstrahlung which occurs when a fast moving electron, or \(\beta\) particle, comes close to and is deflected by the positively charged nucleus of a heavy atom, releasing a photon in the x-ray energy range due to acceleration as predicted by quantum theory. The following description is quoted from Reference 4, page 17. “By placing a high Z material in close proximity and applying voltage to cathode and anode, the average beta energy and number of beta rays striking the anode can be controlled. The photon emission from the cathode is thus modified by the amount of voltage applied to the target. The rate of emission is very sensitive to the energy of the betas striking the anode. With no voltage applied, the source behaves like a conventional encapsulated source.” Thus the origin of the name, VIBS (Variable Intensity Bremsstrahlung System). The size and weight is reasonable. A typical unit is approximately one inch in diameter, two inches long and weighs several ounces. The system requires a high voltage (~50 kv). However, the power level is low (typically several milliwatts).

One of the early problems in developing nucleonic gaging was the use of a scintillation-PM tube detector. PM (Photo-Multiplier) tubes have drift problems and are difficult to calibrate. Currently, a new solid state detector material is under development by several companies. This material, cadmium telluride (Cd-Te), is expected to be more stable, more efficient, and have a greater temperature range than previous detector material such as silicon, germanium, and sodium-iodide. TRW is currently evaluating Cd-Te detectors at cryogenic temperatures\(^\dagger\) that have been developed by Hughes Research and Tyco. The greater efficiency would permit smaller source intensity and reduce the health hazard problem for the high density LOX.

Nucleonics for zero-g gaging appears promising, but some major problems have yet to be overcome. This method x-rays the contents of a tank without phase discrimination. Hydrogen, for example, has a very high gas/liquid density ratio, about 0.04 at 30 psia, and 0.1 at 60 psia for saturated gas/liquid. If the pressurant is helium, this problem would be compounded. In the MDAC-West concept for the EOS (Earth Orbit Shuttle), the Orbiter auxiliary tanks will have autogenous pressurization, meaning \(\text{GH}_2\) for the \(\text{LH}_2\) tank. During long coast in orbit the tanks with high performance insulation, the ullage gas temperature should be close
to saturation and the ullage gas density could be accounted for. However, when the tank is pressurized with warm gas the ullage gas density will be difficult to determine. Consequently, as the tank empties, the error due to the unknown density of the ullage gas becomes larger until the tank empties and the error is entirely related to the ullage gas density ratio. If the gas temperature increases three times above the saturation temperature, the density ratio may range from 0.02 to 0.06 generating an error of about ±2 percent. Furthermore, nuclear disintegration follows the Poisson distribution function where the deviation is a function of count rate, n, and integration time, t:

\[ \sigma = \sqrt{nt} \]

When the deviation is divided by the total count, the error becomes:

\[ \text{Percentage of error} = \frac{\sigma}{nT} \times 100 = \frac{100}{\sqrt{nt}} \]

The detected count increases as the tank empties providing a more accurate determination for a fixed detection time. Thus, the detector becomes more accurate, but the ullage gas error increases as the tank empties. Unless some method is developed that can determine the average gas temperature, an accuracy of ±2 percent may be an ambitious goal for zero-g gaging LH₂ with nucleonics.

Radio Frequency (RF) Resonance

A large tank containing a liquid which is a good dielectric, a property of LOX, LH₂, and kerosenes, can be used as a transmitter whose tuning is a function of liquid quantity. Test results of this method were reported by a Russian academician, B. N. Petrov, in 1962. A wire loop antenna was set up inside the ullage and connected to measurement circuitry. This report indicated accuracies similar to capacitive methods and that surface agitation or tilting the container had insignificant effects.

RF resonance has been studied in this country for zero-g application since about 1963. Currently, the main contractor in this field is Bendix, and the bulk of the material studied has been supplied by that company to the author. The original concept was to pump microwave energy into a tank, considering it to be a resonant cavity whose resonant frequency is a function of volume and the dielectric constant of the material inside. This method looked promising and the Project Thermo study contracted by MDAC-West recommended that this method be included as part of a zero-g gaging experiment. Project Thermo proposed using a S-IVB stage to study cryogenic propellant behavior in a zero-g environment in earth orbit, but funding for the actual hardware never materialized. The Bendix Phase B Final Report was published in 1968 and NASA decided to let a follow-on contract to study a different RF gaging principle. Unwanted resonant frequencies and problems with resonant frequency shifts due to propellant slosh caused this change in design.

The new method involves counting the number of resonant modes when the RF frequency is swept through a fixed band, approximately every 20 milliseconds. An empty tank has a fixed pattern of modes and when the tank is filled with a dielectric fluid, all resonant modes tend to move to lower frequencies increasing the number of modes in the band. Microwave frequency in the area of 1 to 4 GHz is used at a power level about 30 to 100 milliwatts. Figure 2 shows a diagram of the system.

The size and weight of this system can be estimated from the specifications of a flight test system prototype. The test tank is a 5.8 ft³ spherical dewar designed for LOX. The electronics package is 5 inches by 5 inches by 4 inches and shall not exceed 7 lbs. The maximum power is 8 watts, supplied from a 28 vdc power supply. The probe design will vary, but in general terms it could be described in inches. The electronics equipment should not be dependent on tank size; the RF power is low and the processing equipment should be the same.

The design system accuracy is ±0.5 percent from 0 to 10 percent liquid quantity and ±1.0 percent from 10 to 100 percent liquid quantity. Actual test data with LOX with the 30-inch flight test tank has indicated ±4 percent below 20 percent liquid quantity and ±8.5 percent accuracy at higher levels. Theoretical studies based on the analysis of tests lead Bendix to the conclusion that the RF gaging system is independent of propellant location within the tank to a degree sufficient to meet the basic sensitivity and accuracy design goal of ±2 percent of full tank mass content.” The ±2 percent goal seems more practical than the flight test tank requirement of 0.5 percent to 1 percent.

Breadboard hardware development is under contract to NASA/MSFC to provide hardware for a 1/10-scale and a full-scale S-IVB tank. NASA plans to test the full-scale hardware on a stainless steel S-IVB “battleship” test stage in June 1971. Recent tests (March 1971) with the 30-inch LOX tank at Bendix have shown improved results according to both NASA and Bendix engineers. The improvement is primarily due to changes in detection electronics which reduce noise, and to improvements in antenna design.

The RF zero-g gaging system has many attractive features for the potential user. The equipment is lightweight and relatively low powered. The single antenna provides a very simple sensor system. The same concept can be used for kerosenes, LOX, and LH₂. Since these three propellants will be used on the Space Shuttle, RF gaging will have the advantage of commonality.

Resonant InfraSonic Gaging System (RIGS)

A schematic representation of the principles of RIGS operation is shown in Figure 3. This system is essentially a low frequency loud speaker (infraSonic, below 10 Hz) with an attached mass which is driven over a variable frequency until resonance is achieved. Resonance is determined by the pressure oscillations, measured in a small reference volume, minimizing and their phase shifting. The system electronics uses the output of the pressure transducer to control and maintain the driver frequency at the point where the pressure is minimum and the phase shift is 90 degrees. The resonant frequency is typically very low, in the region of 1.0 to 0.5 Hz for large tanks. For low frequencies it can be shown that the wave transmission through the gas is a function of γ and
ullage pressure. The ullage volume becomes a function of the ullage pressure, $\gamma$ and the resonant frequency $f_r$:

$$V_u = \gamma \frac{Pu}{M} \left( \frac{A}{2\pi f_r} \right)^2$$

It can be seen that the ullage volume is directly proportional to $\gamma$. For a LOX tank with autogenous pressurization, as the EOS Orbiter auxiliary tank, the variation in $\gamma$ would be about 2 percent (at 3 atmosphere). However, if helium were used as a pressurant, the variation might be as high as 10 percent.

RIGS is a variation of the acoustical gauges developed by Acoustica Associates and was developed by TRW as a zero-g gaging system for storable propellants. Prototype hardware was designed for the Apollo SPS tanks that weighed 38 lbs and required 28 watts of power. In order to keep liquid off the follower diaphragm with a random liquid orientation, an additional bladder was used to distribute the pressure pulse to the tank cavity. Transfer through such a diaphragm was tested with an inverted tank filled with water. The data from both inverted and upright positions were within ±1 percent of the expected curve. However, RIGS was not developed in time for Apollo application.

RIGS appears feasible for use with LOX tanks, providing materials can be found that are compliant at LOX temperatures. Use with LH$_2$ does not appear feasible because of the compressibility of LH$_2$ and the extreme low temperature. Accuracy better than ±2 percent seems likely.

**ZERO-G GAGING REQUIREMENTS**

Review of contract proposals and progress reports reveals that design requirements for accuracy commonly specify 0.5 percent. Realistic evaluation indicates that 2 percent accuracy is probably an ambitious goal. However, the accuracy requirements for zero-g gaging may have been overemphasized. Highly accurate propellant gaging for increased payload is only relevant to ground loading and main engine closed loop propellant utilization, with both cases occurring only in a conventional g field. Zero-g gaging should only be required as a monitor for go/no-go situations where lower accuracy is acceptable. Simple level sensors are sufficient for loading, and the capacitance probe is the best device for closed-loop propellant utilization.

For future designs such as the nuclear Shuttle, propellant transfer from the earth orbit Shuttle is one design consideration. The transfer is to be accomplished under a low acceleration ($2 \times 10^{-5}$ g). The S-IVB flight experiment has shown that this low acceleration is sufficient to settle cryogenic propellants. Gaging in this situation could be accomplished with level sensors. However, some problems would exist because the LH$_2$ would have a meniscus of about 20 inches due to surface tension forces. In this case an ultrasonic liquid level sensor might be used since the attenuation of the ultrasonic energy would make the sensor insensitive to thin layers. Using a small thrust to settle the propellants is not unreasonable. The 295,000 S-IVB/payload combination has propellants settled by a thrust smaller than 15 lbf for the translunar injection burn restart. Actually, zero-g gaging works better with a settled propellant where ullage temperature can be measured.

**CONCLUSIONS**

Consideration of zero-g gaging methods should be influenced by the knowledge that this convenience sacrifices accuracy. RF gaging looks promising with large cryogenic tank tests forthcoming in Summer 1971. Nucleonic gaging for LH$_2$ and RIGS for large LOX tanks are the next best choices. If the VIBS X-ray device is proven, nucleonics may prove feasible for LOX tanks. Zero-g gaging systems are not competitive with the present capacitance probe or point level sensors for closed-loop propellant utilization or ground loading. The zero-g gaging systems with their expected 2 percent accuracy should be acceptable for inflight monitoring. Low thrust propellant settling can provide an alternative solution to zero-g gaging or improve the accuracy of such a system. Indications are that NASA and USAF are combining forces to make 1971 the year of decision for zero-g propellant gaging.

**NOMENCLATURE**

- A - area or RIGS weighted diaphragm (Figure 3)
- B - Compton scattering buildup factor
- $f_r$ - resonant frequency
- I - intensity of radiation detected (disintegrations per sec per cm$^2$)
- $I_0$ - source radiation intensity (disintegrations per sec per cm$^2$)
- M - mass of attached weight on RIGS weighted diaphragm (Figure 3)
- Pu - ullage pressure
- Vu - ullage volume
- $V_r$ - reference volume
- n - average nuclear disintegration rate (events per sec)
- t - nuclear detection time (sec)
- x - thickness of radiation absorber in cm
- $\gamma$ - ratio of specific heats - $C_p/C_v$
- $\mu_m$ - X-ray and gamma-ray mass absorption coefficient

**ACKNOWLEDGEMENT**


The technical information presented is a survey of the work of specialists in the various fields of zero-g gaging and resulted from
their cooperative efforts. Program Managers Rod G. Morrison and Rim A. Kaminskas, TRW Systems Group - Nuclear Dept., have been very helpful in supplying documents and discussing the general field of zero-g gaging and nucleonic gaging, respectively. Additional information concerning basic nucleonic concepts has been supplied by Sam C. Dominey, Assistant General Manager, General Nucleonics Division, Tyco. Information concerning RF gaging has been coordinated by Mr. B. J. "Bing" Dagastino, Western Regional Manager, Bendix Instruments and Life Support Division.

REFERENCES


9. Ibid - P 4-8 to 4-15.

10. Ibid - Figure 3-11.

11. Ibid - P C-3.


13. Ibid - Section 2.


15. Ibid - P 5-12.


Figure 1. VIBS Showing Method of Controlling Bremsstrahlung Output

*BAPENT APPLIED FOR. DEVELOPED BY TRW UNDER INTERNAL RESEARCH AND DEVELOPMENT PROGRAM, APRIL 1970.
Figure 2. RF Mode Counting System
Figure 3. RIGS Schematic

COURTESY TRW, SYSTEMS GROUP