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ANALYSIS OF RP-1 FUEL DENSITY FOR OPERATIONAL ATLAS MISSILES

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SUMMARY

One of the factors which must be known for accurate prediction of performance of ballistic missiles like the Atlas, Titan, and Thor is the weight of tanked propellants. This is especially important when there is no propellant utilization system and the residuals at the end of the flight, and therefore the maximum range, will be a function of how well the propellant weights were predicted. Perhaps the most important factor which enters into this weight prediction is the fuel density. This paper analyzes the effect of temperature and manufacturing processes on fuel density.

Density information was obtained from shipment records of the major oil companies who supply RP-1 to the Air Force. Although the nominal specifications were met, a statistical analysis of these shipments indicated that the means, standard deviations, and distribution functions differed significantly from what would be expected using the specifications alone. Since the engine manufacturer may be supplied by one company, the test site by a different company, and the operational sites by still a third company, the analyses of test data must take the fuel density variations into account.

Another factor which affects fuel density is the temperature at which the fuel is stored. Since there are a number of different Atlas site configurations involving above-ground storage, buried tanks, and air-conditioned silos, the temperature effects must be calculated on a site-by-site basis. Tables are presented which combine these effects with manufacturers' data to yield mean fuel density and standard deviations as functions of site location. They should prove useful for targeting, propulsion analysis, and other areas where accurate simulation of propellant characteristics is required.

I. API VARIATIONS

A. Density Data

One of the factors which must be known for accurate prediction of engine performance for ballistic missiles like the Atlas, Thor and Titan is the density of the fuel. This is especially important when there is no propellant utilization system, and the residuals at the end of the flight will be a function of how well the propellant densities were predicted. This makes the maximum range of the weapon system a direct function of the accuracy to which these densities are known.

The two factors which affect the density of the RP-1 (kerosene) fuel used in these missiles are the temperature and the specific gravity. The index which is used to measure the specific gravity of the fuel is the API number (American Petroleum Institute). The fuel density is calculated using the formula:

$$\rho_F = 50.41 - \left[0.026\ (T_F - 60) + 0.290\ (API - 43.5)\right] \qquad (1)$$

where:

ρ_F = Fuel Density (lb/ft^3)

T_F = Fuel Temperature ($^\circ$F)

API = API Index (degrees)

Specifications covering purchase of RP-1 for the Air Force require an API number between 42.0 and 45.0 degrees. For the Atlas system in particular, there are three major suppliers who provide RP-1 to all of the test stands and operational sites. Each tank which is delivered is accompanied by a certificate stating the API number as determined by laboratory tests of samples taken from the tank by the manufacturer. The sampling technique is discussed in detail in the appendix.

Various quality control groups within the Air Force monitor the fuel prior to its arrival at a given site, and additional density checks are frequently made. Figure 1 shows the major offices concerned with fuel purchase and quality control for the Air Force. In California, Socony-Mobil supplies all of the RP-1 used at sites such as Vandenberg AFB, Edwards AFB and Santa Susana. Control is through the Los Angeles Air Procurement District and the Resident Inspector of Navy Materiel at Long Beach. Tidewater Oil Company also supplies shipments to Fairchild AFB and Cape Canaveral and control is handled through the Resident Inspector of Navy Materiel in Concord, California. All of the other Atlas sites are contracted to be supplied from Bell Oil and Gas in Granfield, Oklahoma and monitored by the Wichita Air Procurement District in Oklahoma City. Records of all shipments are sent to the Directorate of Petroleum and Chemicals at Middletown, Pennsylvania. To obtain information on mean densities and dispersions at the various Atlas sites, records were obtained from the three major suppliers covering shipments of RP-1 from January, 1960, to May, 1961. The total amount of data obtained was as follows:

Socony-Mobil	21 tanks
Tidewater Oil Company	64 tanks
Bell Oil and Gas	74 tanks

Each of these tanks corresponds to a total bulk volume of from 2000 to 5000 barrels of fuel. Thus each tank could be used to fuel up to eleven Atlas missiles. Although all shipments meet the specification on API, a calculation of the mean API and standard deviations for each of the three suppliers shows surprisingly wide differences. This is illustrated in Figure 2 where the frequency distributions of API for the three suppliers are compared graphically, normalized on a percentage basis. The first supplier, Socony-Mobil, shows an API distribution which is nearly uniform and closest to the assumed distribution using the specification values. The mean, however, is an API of 43.0 degrees, which is less than the assumed mean of 43.5 degrees. The second supplier, Tidewater Oil Company, has a mean close to the expected value but a standard deviation which appears considerably smaller than that implied by the specification. Finally, the last supplier, Bell Oil and Gas, has a mean which is extremely different from either of the other two and a dispersion considerably smaller than expected. The data for all of the above are summarized in Figure 3 and include the destinations for all of the shipments. In order to verify that the fuel stored at the sites had characteristics similar to that being supplied, independent data on API measurements were obtained from 124 Atlas tanking tests at AMR and 24 pad storage samples from Vandenberg AFB. As can be seen from Figure 4, these distributions are quite similar to those of the respective suppliers.

B. Analysis of API Variations

There are two major factors which contribute to the API variations observed. The first is the variation in chemical and physical properties of the crude oil from which the RP-1 is manufactured, and the second is the difference in the manufacturing process. These seem to account for wide variations shown in Figure 2 as follows:

Socony-Mobil uses a wide variety of crudes, partly from their own fields in Los Angeles, and the rest from other parts of the United States and a number of foreign countries. This results in an API for each production run which may be considerably different from the previous one and tends to give a uniform rather than normal distribution. Tidewater Oil Company obtains its crude oil almost exclusively from a single oil field near Ventura, California, and thus the API is normally distributed, reflecting the normal variations expected in the crude oil from this single source. Bell Oil and Gas also gets its crude oil from a single major oil field, but in this case the physical properties of the crude oil are such that unless the API number is high, the resulting RP-1 will not meet the specification on freezing point temperature. Since the API specification requires a maximum index of 45.0 degrees, the manufacturing process is controlled to a high degree, such that the API falls between these limits. This results in an average API number of 44.9 degrees and a spread of only ±0.1 degree.

In applying these results to a weapon system such as the Atlas, one should recognize the sequence used in deriving flight test parameters and performance data. Rocket engine calibrations are normally carried out at the Rocketdyne Test Facility in Santa Susana. Flight test results from both AMR and PMR are then analyzed and the resulting data applied to operational sites. It is quite apparent that if there is considerable variation in RP-1 density at each of these facilities due to API variation alone, this may have a serious effect on the predicted missile performance. It thus appears more reasonable to use the manufacturer's data and predict fuel density on a site-by-site basis, rather than using a value derived from the contract specification. The other major factor which affects RP-1 density is the temperature, and this will be discussed in the next section.

II. TEMPERATURE VARIATIONS

In computing the effect of temperature on density, the fuel storage conditions must be considered. At a number of Atlas sites the fuel storage tanks are exposed. The nominal fuel temperature will therefore be that of the ambient air, and dispersions will be a function of the variations in air temperature. The fuel temperature will also lag that of the air due to the heat capacity of the large bulk of fuel. At other Atlas sites the fuel tanks are buried. The fuel temperature thus becomes a function of the tank depth and the heat transmission coefficient of the surrounding soil, as well as the mean air temperature and its dispersions. If the frost line depth and soil characteristics at a given site are known, it is possible to calculate fuel temperatures fairly accurately. At some sites the average tank depth is such that for variations corresponding to the worst weather conditions, the fuel temperature variation at this depth is less than $0.3^{\circ}F$ (one sigma). The third major site configuration is the silo, which is temperature controlled to $70^{\circ} \pm 5^{\circ}F$. Since the fuel is stored in the missile fuel tank itself, the fuel temperature will correspond to the same variations as that in the silo. This is equivalent to a rectangular distribution with a standard deviation of $\sigma = 2.89^{\circ}F$.

III. OPERATIONAL FUEL DENSITY

Using Equation (1) of Section I, the mean densities and standard deviations were computed for Cape Canaveral and each of the 13 operational sites. The results are summarized in Figure 5.

Note that the final density values for each site differ radically depending upon the combination of API distributor and fuel storage facility. In no case does the mean density value and dispersion agree with the specification values. Since the missile maximum range performance is a function of these density values, there appears to be justification in using different values for each site for targeting as well as propulsion analysis and other areas where accurate simulation of propellent characteristics is required. It should be further noted that a continuous monitoring of fuel density is required, since major changes in the suppliers of RP-1 in the future can grossly affect the density characteristics.

APPENDIX

The procedures for measuring RP-1 API follow the ASTM Standards on Petroleum Products which appear in Volume I, 37th Edition 1960, Page 150.

To determine uniformity, four samples are taken; two feet from the top of the liquid level, at the center, two feet from the bottom, and eight inches from the bottom. If the variation between any two readings is greater than 0.2 degrees of API, the tank is rejected as being nonuniform. If the tank is uniform, a running sample is then taken using a weighted container and cork. These are lowered to the bottom of the tank, the cork removed and the container pulled upward at a uniform rate. If the container is between 75 percent and 90 percent full, an API determination is run. If the sample is not within this volume, it is rejected and a second sample taken.

The API is measured with a hydrometer whose repeatability is 0.2 degrees of API when the same person repeats the measurements. Specifications call for a lab-to-lab repeatability of 0.5 degrees of API, but in practice the actual repeatability for all samples runs between 0.1 and 0.2 degrees API. The sample is usually chilled to 60°F or measured at a different temperature and a correction applied. Each time the RP-1 is transferred to a different tank, tank cars or trucks, additional samples are taken. The API is also checked at the launch sites using local facilities, and samples are periodically sent to government laboratories for further testing.

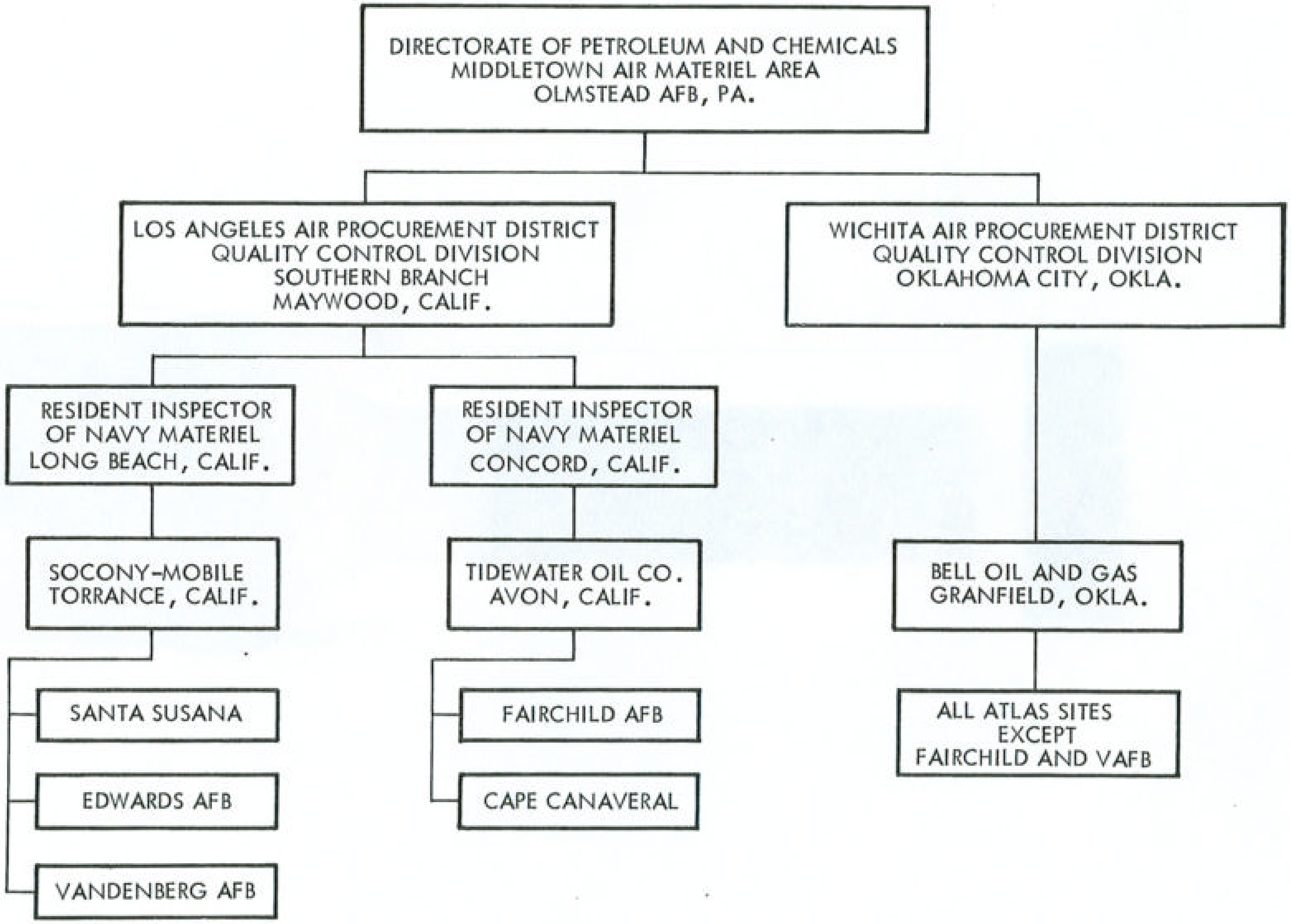

Figure 1. RP-1 Quality Control Structure

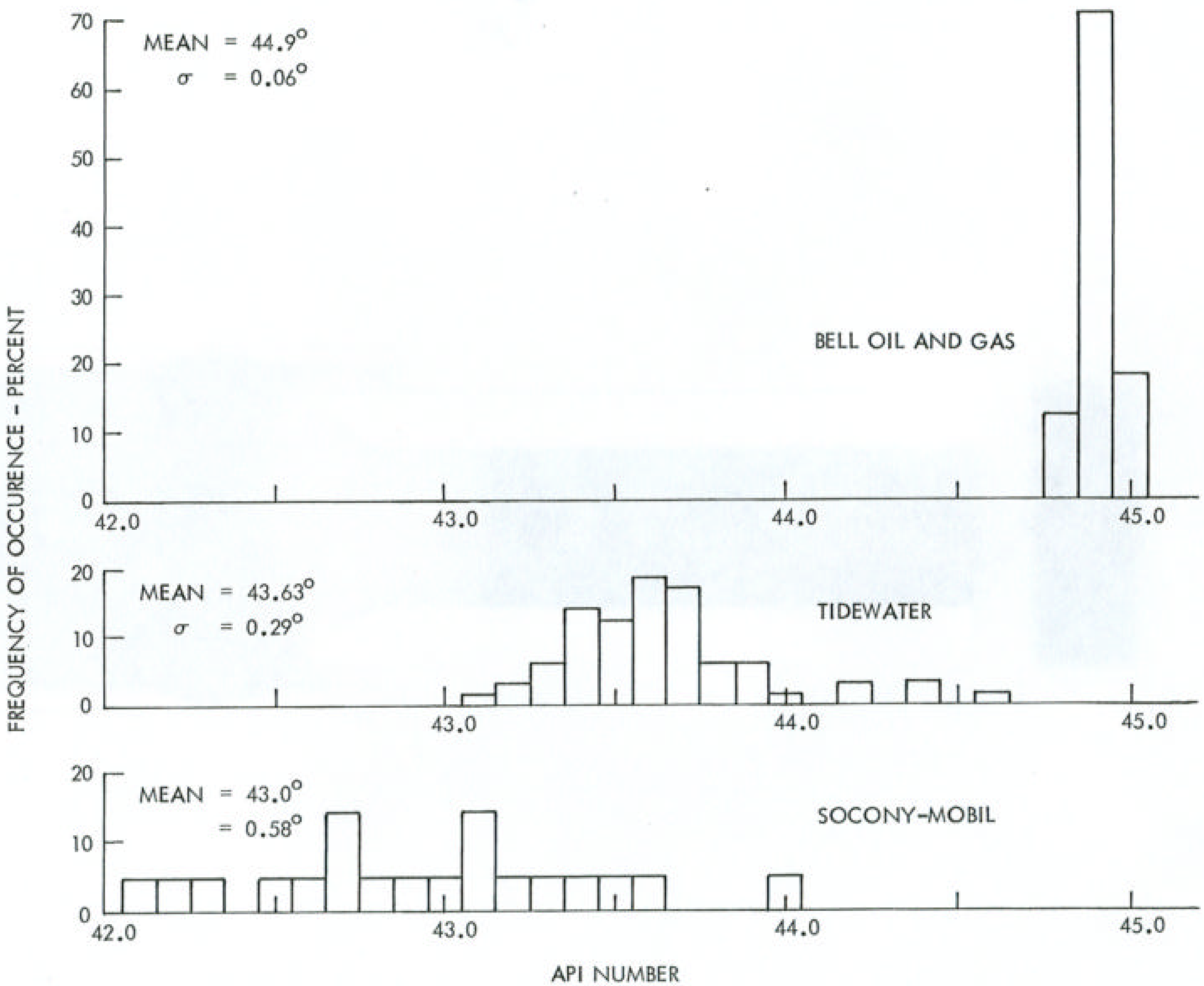

Figure 2. API Distribution of Major RP-1 Suppliers

Supplier	Mean API	Dispersion (1σ)	Number of Samples	Destination
Socony-Mobil	43.0	0.58	21	Edwards AFB Santa Susana (Rocketdyne) Vandenberg AFB
Tidewater	43.63	0.29	64	Fairchild AFB Patrick (AMR) Nimbus (Aerojet)
Bell Oil and Gas	44.9	0.06	74	Offutt Altus Dyess Forbes Warren Plattsburg Neosho (Rocketdyne) Denver (Martin) Arnold

Figure 3. Summary of RP-1 API Characteristics

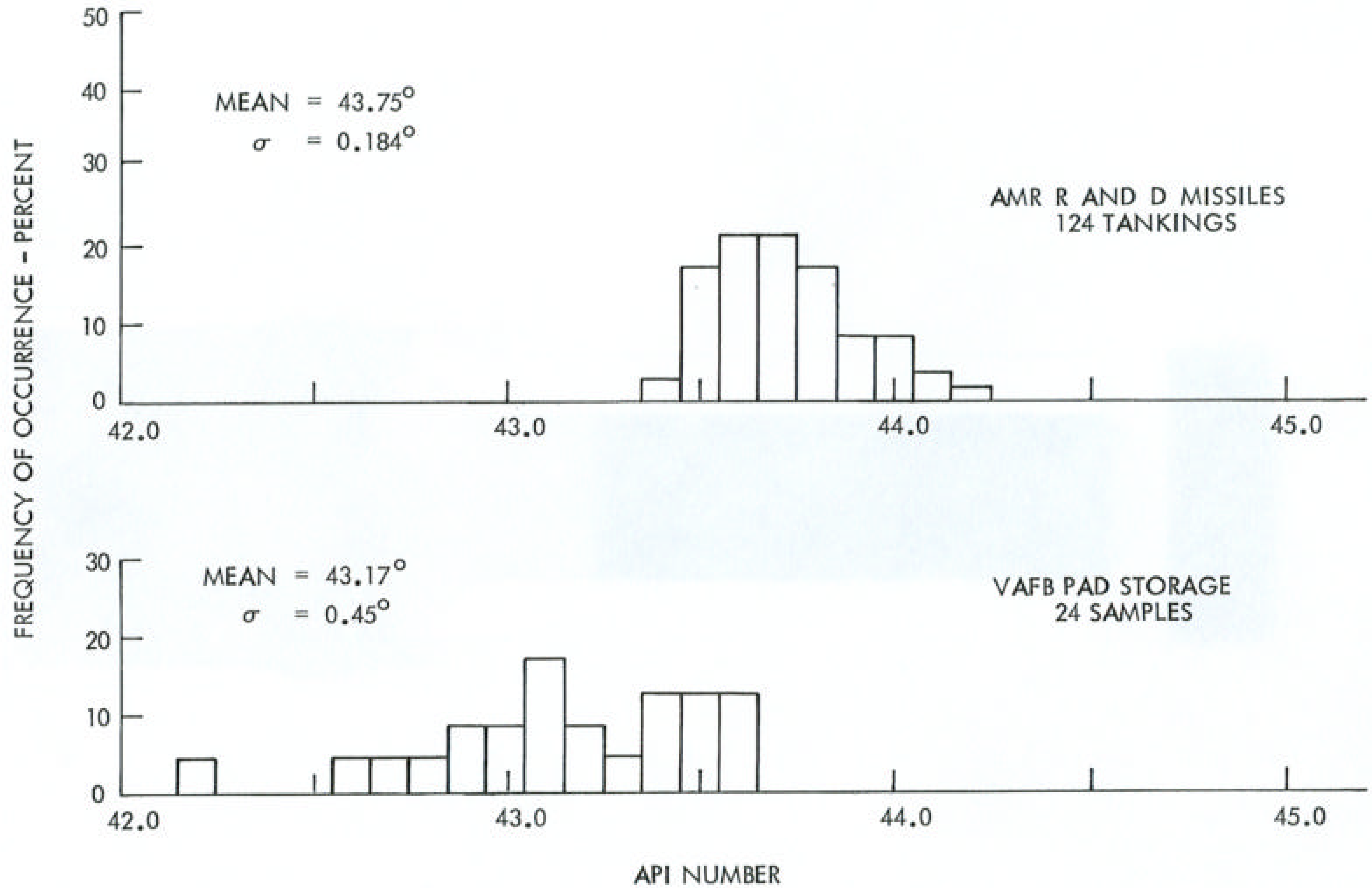

Figure 4. API Distribution of RP-1 at AMR and VAFB

Site	API (°)		Temperature (°F)		Density (lb/ft^3)	
	Mean	1σ	Mean	1σ	Mean	1σ
Cape Canaveral	43.63	0.29	76	9.4	49.96	0.251
Vandenberg	43.0	0.58	60	6.0	50.56	0.225
Warren I	44.9	0.06	45	23.0	50.39	0.580
Warren II	44.9	0.06	45	0.3	50.39	0.019
Offutt	44.9	0.06	50	0.3	50.26	0.019
Fairchild	43.63	0.29	45	0.3	50.76	0.084
Forbes	44.9	0.06	55	0.3	50.13	0.019
Warren III	44.9	0.06	45	0.3	50.39	0.019
Schilling	44.9	0.06	70	2.89	49.74	0.075
Lincoln	44.9	0.06	70	2.89	49.74	0.075
Altus	44.9	0.06	70	2.89	49.74	0.075
Dyess	44.9	0.06	70	2.89	49.74	0.075
Walker	44.9	0.06	70	2.89	49.74	0.075
Plattsburg	44.9	0.06	70	2.89	49.74	0.075

Figure 5. RP-1 Fuel Density at Atlas Sites