NATIONAL BUREAU OF STANDARDS REPORT

9960

COMPATIBILITY OF TANK COATINGS AND MATERIALS WITH LIQUID PROPELLANTS

SUMMARY REPORT

December 1965 Through September 1968

For

Picatinny Arsenal Project

Order No. A1-8-RFO-01-D1-GG

To
Commanding Officer
Picatinny Arsenal, Dover, N.J. 07801
Attn: Code SMUPA DL-2
Liquid Rocket Propulsion Laboratory

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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NBS PROJECT
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By
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U.S. DEPARTMENT OF COMMERCE

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Compatibility of Tank Coatings and Materials with Liquid Propellants

Summary Report of Work Done from December 1965 through September 1968

By the National Bureau of Standards, Washington, D.C. 20234

1. Background of Problem

The high tensile strength (up to 300,000 psi), and hardness of 18% Ni Maraging steel permit fabrications for high pressure use that weigh less and are less bulky than when made from lower density metals. These characteristics are desirable for material from which to make liquid propellant tanks for rockets.

During the Fall of 1965 NBS was asked by Picatinny Arsenal for information on the feasibility of using metallic coatings to protect liquid fuel rocket tanks from corrosion by the fuel and at the same time protect the fuel from catalytic decomposition by the relatively active Maraging steel and minimize formation of metal salts in the fuel that could have an adverse effect on rocket engine performance. Electroless nickel was considered as a likely coating for the interior surfaces of assembled Maraging steel fuel tanks because it could be applied without use of electrodes and without current and its thickness over complex and recessed surfaces was very uniform. Other metals such as nickel, cadmium and silver were also considered because there were conflicting reports of the reactivity of electroless nickel with liquid rocket fuels.(1)

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1. Compatibility of Materials with Rocket Propellants and Oxidizers. DMIC Memo 201, Battelle Memorial Inst., Jan. 1965.

As a preliminary step in the program, several specimens of heat-treated, 18% Ni Maraging steel were coated with electroless nickel, electroplated nickel and tungsten and sent to Picatinny Arsenal for testing and evaluation. Concurrently, a program was initiated at NBS to apply numerous metallic coatings to 18% Maraging steel specimens and to expose these specimens to liquid rocket fuels to determine their suitability for application and use in liquid rocket fuel tanks. The program also included the experimental application of the more promising coatings to one-half scale and full scale liquid rocket fuel tanks for development of methods of application and for further testing of the coatings.

2. Tests for Exposing Coatings on Maraging Steel

It was requested by Picatinny Arsenal that the tests of the coatings and fuel be made at the most rigorous condition that might be expected to occur during storage of missile rocket motors. In storage sheds in the desert, e.g., temperatures of 160°F might be expected to be reached, while in artic regions the temperature could drop to -65°F. Since chemical reactions are usually most rapid at the higher temperatures, the specimens were to be exposed to the fuel at 160°F except for a few tests to be run at room temperature for comparison.

The planned storage life of the rocket motors was about six years. Therefore, exposure tests must be at least of one year duration to be meaningful. Some of the more promising materials were to be exposed to the fuel for longer periods of time.

The liquid rocket fuel to be used in the tests was MHF-3, a combination of hydrazine compounds containing 86% monomethyl hydrazine and 14% anhydrous hydrazine.(2) The fuel would be freshly mixed and sealed with the specimen in a suitable test unit. The test unit would determine the rate of catalytic decomposition of the fuel by measuring the volume of evolved gas or by pressure increase in a closed system. Gas evolution from the fuel is proportional to fuel decomposition and is a critical factor in the storage of fuel.

3. Equipment for Exposure

Many metals cause catalytic decomposition of hydrazine and its derivatives, and many non-metals either react with or are dissolved by hydrazines.(2) Therefore, the materials of the exposure-test units had to be selected carefully. It was found that most of the pipe fittings and gages on the market were made from stainless steels that were reported to be incompatible with the fuel. Glass was inert to the fuel but making joints and valves leak-proof was very difficult.

3.1 Glass Units

Because of the difficulty of procuring metal fittings of the correct composition, the first units were made of glass. Trial and error and the experience gained by other workers(3), (4) resulted in a completely fusion-sealed unit without valves, ground glass joints etc.

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2. The Handling and Storage of Liquid Propellants. Office of the Director of Defense Research and Engineering, U.S. Government Printing Office, 1963.
3. Dr. A. J. Beardell, et al, Thioxotropic Packaged Liquid Propellants, Report RMD 5020-F, Contract No. N600(19)59348 (Navy Bur. Wep.). 1 Oct. 1962 to 30 Sept. 1963, Thiokol Corp., Reaction Motors Div., Danville, N.J.
4. Advanced Packaged Liquid Propellants Research, RMD-5074-Q1, Contract No. 65-6570, 12 August 1965. Thiokol Corp., Reaction Motors Div., Danville, N.J.

These units incorporated a chamber for holding the fuel and the specimen and had an attached manometer to measure any gas released by catalytic decomposition or by reaction with the specimen. A diagram of the unit is shown in Figure 1. Mercury was used for the manometer fluid. Although supposedly reactive with the fuel(2) mercury had been used in contact with MHF-3 by others.(3),(4)

The units were made from pyrex glass tubing. The ends of the specimen chamber were left open for loading the unit with the specimen and fuel. All areas which the fuel vapor contacted were arranged to be below the surface of the constant temperature bath to reduce the transfer of the fuel to the manometer side of the unit by condensation. Only the manometer tube containing mercury protruded from the surface of the bath. A porous frit with holes too small to permit the passage of mercury was installed between the test chamber and the manometer to prevent accidental amalgamation of the specimen. The enlargement in one side of the manometer tube formed a mercury chamber which permitted use of the shallow temperature bath and resulted in a compact unit.

3.2 Metal Units

A source of supply of compatible 304 stainless steel fittings was finally located and several metal test units were assembled with a test chamber machined from solid stock. The units consisted of a test chamber with a bolted cover connected to a bleed valve and a pressure gage as shown in Figure 2. A pyrex glass cup held the fuel and specimen, electrically insulating the latter from the metal test chamber. No gages could be obtained made from 304 stainless steel so gages of 316 stainless steel were used.

The metal units were much more expensive than the all-glass, fusion-sealed units. They were also less reliable mainly because of difficulty in obtaining sufficiently tight valve and cover seals. Only four of the metal units were used for fuel tests at 160°F.

3.3 Constant Temperature Baths

Baths were constructed to maintain the units at 160°F. They consisted of insulated metal or glass tanks with internal spacer blocks to position the units during the test. Several fluids for the baths were considered but water was decided upon for reasons of safety.

4. Tests of Coatings in MHF-3

4.1 Preparation of the Specimens

Small specimens (15 cm^2) were used for the testing of a number of coatings and some other materials. Specimens to be plated were cut from Maraging steel sheet which had been heat-treated. The surface was chemically or mechanically descaled, electropolished and given a nickel strike before being plated with the coatings to be tested. The strike was necessary because the inherent passivity of Maraging steel prevents the adhesion of deposits unless special procedures are used.(5) It consisted of acid nickel chloride solution which was more reactive with the Maraging steel surface than standard plating solutions. The strike bath was used for plating the specimen for only about one minute after a one minute immersion. The various deposits were immediately applied over this very thin nickel coating. After plating, the specimens were carefully rinsed and dried. They were weighed before and after plating to check deposit thickness and establish a basis for determining loss of weight due to corrosion by the fuel.

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5. G. DiBari (International Nickel Co.) Plating 52, 1159 (1965)

4.2 Loading of Test Units

The units were loaded through the open bottom of the tube forming the specimen chamber. After placement of the specimen, the bottom of the chamber was sealed by fusing and drawing the glass, then cooled and flushed with dry nitrogen. The narrow top of the specimen chamber, through which the fuel would later be loaded, was then sealed by fusion. The units were pumped down to a low pressure and all the seals were checked with a spark type, high voltage leak tester. The mercury was then added to the manometer and the units pressurized to the limit of the manometer tube with nitrogen as an added leak check of the entire unit. After ten days to two weeks, if no leak was shown by a drop of the mercury column, the units were opened by breaking the seal at the top of the specimen chamber and the fuel added to cover the specimen. A plastic syringe attached to a long, flexible Teflon tube was used to introduce the fuel to the lower end of the bulb. A temporary closure was then made with Teflon tubing. This charge of fuel was left in place about a week to flush and precondition the specimen and interior surface of the unit. The fuel was then removed with the syringe and replaced with fresh fuel. The filling tube was then resealed by fusion, after which the unit was flushed with nitrogen to remove air introduced during sealing. This was accomplished by pushing a small Teflon tube through the mercury into the chamber above the mercury and through this tube successively pressurizing with nitrogen and then bleeding several times. After inspection of the seal under magnification, to check for complete fusion, the unit was placed in the constant temperature bath to begin the test. The metal, bomb-type units were leak-checked, loaded and flushed with nitrogen in similar steps. Loading of fuel was done in a fume hood with the necessary protective

gloves, clothing, and transparent shielding.(2)

5. Exposure Tests

5.1 Measurement of Evolved Gas

The glass manometer type units had a centimeter scale attached to the manometer tube which allowed reading the change in the height of the mercury column which indicated changes in the pressure and volume of the gas evolved from the fuel. Evolved gas in the bomb type units was indicated by an increase in the gage reading.

5.2 Calculation of Rate of Fuel Decomposition

The rate of fuel decomposition was expressed in terms of the volume of gas evolved in a given time, or in terms of the pressure developed in a given time in a tank of defined size and ullage(6).

For the glass units, both pressure and volume change as gas is evolved by decomposition of the fuel. The equation:

$$\Delta V = \frac{V_2 p_2 - V_1 p_1}{p_a} \qquad (1)$$

gives the amount of gas evolved, measured at atmospheric pressure (p_a), where V_1 and V_2 are initial and final total volume in the unit and p_1 and p_2 are initial and final pressure, respectively. The volume of the zero point of the manometer was determined from initial calibration of the unit. From this value and measured shift of manometer level, V_1 and V_2 were calculated. Height of the mercury in the manometer plus atmospheric pressure yielded values of p_1 and p_2. The amount of gas evolved as calculated from equation (1), is due in part to decomposition at the surface of metallic specimen, due to its

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6. V. A. Lamb, et al, Surface Protection of Maraging Steel, NBS Progress Reports Nos NBS 9377 and NBS 9638. Contract No. A1-8-RF034-01-D1-GG, Picatinny Arsenal, Dover, N.J.

catalytic effect, and in part from inherent tendency for the fuel to decompose at other locations, e.g., in the liquid itself, in the vapor phase, and at the glass fuel interfaces. The latter are referred to as "background decomposition". The "background" has been determined in identical units except that no metal specimen was present. V, due to background decomposition, which was found to be very small in the case of MHF-3 in glass units, is subtracted from V of equation (1) to obtain the amount of gas evolved due to the effect of the metallic specimen itself.

For the bomb-type units,

$$\Delta V = \frac{V_1 (p_2 - p_1)}{p_a} \qquad (2)$$

In this case, the initial gas volume in the unit, V_1 is constant.

Since the rate of gas evolved due to contact of a given metal with the fuel will be proportional to the area of the metal and to time of contact, reactibility may be expressed in terms of a single coefficient defined as rate of gas evolved per unit area per unit time, or

$$\text{rate coefficient} = \frac{\Delta V}{(\text{area})\ (\text{time})} = \text{cm}^3/\text{cm}^2/\text{day} \qquad (3)$$

The rate of decomposition has also been expressed in terms of tank pressure after one year, assuming a one cubic foot tank with 10% ullage, and with the entire inner surface active. Pressure in this assumed tank will obviously be proportional to the rate coefficient defined previously. It can be shown that the relationship is:

$$P_{y,g} = (10560)\ (\text{rate coefficient}) \qquad (4)$$

where $P_{y,g}$ is gage pressure in psi after one year. The numerical factor takes account of tank surface, ullage, and conversion of the rate coefficient from metric units to psi. In a tank with 5% ullage instead of 10% ullage the pressure would be doubled.

The above relationships are all based on the simple gas laws. The calculations of ΔV, rate coeficient, and $P_{y,g}$ are laborious, especially when as many as 50 units are under test at one time. Manual calculations for three months of data from 30 units required approximately two man-weeks. The calculations have therefore been programmed for the computer and require only about 8 hours to punch on tape and to calculate the data from 50 units.

6. Results of Tests of Specimens Exposed to MHF-3

It was initially considered that a test for the duration of one year would be sufficient to give reliable data on a given specimen. Later it was decided to run several of the more promising materials for a longer period because rate changes after prolonged exposure occurred in a few cases. However, enough data has been accumulated to give the initial performance of the various materials tested.

Most of the tests were run on specimens consisting of a metallic coating on 18% Ni Maraging steel. Some uncoated materials such as bare Maraging steel and several stainless steels were also tested.

6.1 Room Temperature Tests

Three metallic coatings on Maraging steel plus bare Maraging steel were exposed at room temperature. The lowest rates were obtained with cadmium and zinc while cobalt caused nearly as much decomposition of fuel as did the bare Maraging steel.

Rate curves for these specimens are shown in Figure 3. In calculated tank pressure per year, the spread was from 51 psi for the cadmium coating to 432 psi for bare Maraging steel.

6.2 Tests at 160°F

The tests run at 160°F approximately corroborate the findings at room temperature, except for cobalt, which accelerated to nearly ten times that for bare Maraging steel. Rate curves for several of the coatings and materials are shown in Figure 4. The slightly lower rates for cadmium and zinc at 160°F was attributed to the formation of a protective oxide film at the higher temperature. Bar graphs for these and most of the other specimens tested are shown in Figure 5. Grouped according to rate of fuel decomposition, the various coatings and materials are as follows:

Low Activity:	0 to 80 psi/year calculated tank pressure - silver, cadmium, standard electroless nickel, zinc, tin-nickel alloy, tin, lead, tungsten, 50/50 lead-tin solder, 347 stainless steel, aluminum foil, and two titanium alloys, 6 Al - 4 V and 3 Al - 11 Cr - 15 V.
Moderate Activity:	80 to 250 psi/yr - gold, nickel, stainless Maraging steel, electroless nickel from the proprietary borohydride bath, chromium, and Teflon coated Maraging steel.
High Activity:	250 to 10,000 psi/yr - Cobalt, 19% Maraging steel, molybdenum, iron, electroless nickel from the alkaline bath, AM-355 stainless steel and Inco - 718.

6.3 Supplementary Experiments with MHF-3 Fuel

6.3.1 Porosity Tests

Tests were made to determine the effect of porosity in coatings of silver and cadmium on Maraging steel exposed to MHF-3 at 160°F. Simulated pores were made in the coatings by drilling through the coatings

just deep enough to expose the Maraging steel. Pore diameters ranged from 0.013 inch to 3/8 inch. The decomposition rates were calculated on the basis of the area of Maraging steel exposed by the pores. It was found that the rate of fuel decomposition is roughly proportional to pore area. Fuel exposed to the Maraging steel-silver couple decomposed at a higher specific rate, based on the exposed area of Maraging steel, than that exposed to Maraging steel alone. The contrary effect, occurred with the cadmium plated specimen. The rate of gas evolution, based on the area of Maraging steel exposed, was smaller than that for Maraging steel alone. It is hypothesized that there may be a bimetallic, electrolytic effect, the cathodic silver exerting an accelerating effect and the anodic cadmium a protective effect.

6.3.2 Effect of the Ratio of Area of Metal to Volume of Fuel on MHF-3 Fuel Decomposition

Units were set up which contained 100 cm^2 of nickel surface compared to about 15 cm^2 for the usual specimen tested. The decomposition rates at 160°F showed that, for a range of area/volume from 0.5 to 6.8, there was no significant difference in the rate coefficient of fuel decomposition.

6.3.3 Decomposition Rate of Surface Area and Fuel Volume

Experiments were designed to show the effects of glass or metal areas and fuel volume on the rate of fuel decomposition designated as "background rate". It was found that the glass-vapor interface and the liquid-glass interface area have a negligible effect on decomposition of the fuel. The dominant factor in "background" decomposition is the volume of the fuel. That is, self-decomposition in the liquid phase. This rate is, however, very small, of the order of 0.0002 cm^3 of gas/day/cm^3 at 160°F.

6.3.4 Effect of Contact Between Metal and Fuel Vapor

The fuel decomposition rate of a Maraging steel specimen exposed at 160°F to the fuel vapor phase only, was initially very low. But the rate gradually increased to more than 60% of that for contact with the liquid. This indicated that condensation of liquid on the metal surface became an important factor with increase in time.

7. Results of Examination of Specimens and MHF-3 Fuel After Tests

A number of the tests that had run for a year or more at room temperature and at 160°F were discontinued. The units were disassembled carefully and the fuel and any corrosion products were retained for examination.

7.1 Corrosion of Metals

Electroless nickel on Maraging steel showed no loss in weight of the coating while zinc was the most severely corroded of the metals tested. Both cadmium and nickel underwent appreciable corrosion and some other metals a lesser amount. In the case of the nickel there was a tendency toward pitting on some specimens. This attack occurred both at room temperature and at 160°F. The cross-section of a nickel-plated, welded Maraging steel specimen showed good coverage of the nickel over the weld. The following metals had no weight loss or, at most, a few milligrams, which corresponded to the loss of a few microinch in thickness: cobalt, Maraging steel, lead, tungsten, tin-nickel alloy, tin, iron, molybdenum and silver. The concentrations of metal salts that were dissolved in the MHF-3 fuel are shown in Figure 8.

There was no correlation between the activity of a metal in accelerating decomposition of the fuel and corrosive attack on the metal. Thus, bare molybdenum, one of the most active decomposers of fuel, was uncorroded, while zinc, one of the least active, was severely corroded.

Standard electroless nickel had a low activity and was not corroded.

In the special porosity tests, only the silver plated specimens have been examined to date. A cross section of one of the drilled "pores" showed slight corrosion of the exposed Maraging steel at the sides of the pore beneath the silver, causing slight undercutting and enlargement of the pore cavity in the Maraging steel.

7.2 Effects of MHF-3 Fuel Used in Tests

In cases where corrosion occurred, there was discoloration of the fuel or a precipitate or both. This was caused by the salts formed due to dissolution of the metal involved. The concentrations of the dissolved salts were evidenced by a coloring and darkening of the fuel and were determined by evaporating a known volume of fuel and weighing the residue. These values ranged from 0.02 g/l for silver through 0.27 for zinc to 16.3 g/l for the fuel from a nickel plated specimen in the form of a Maraging steel tube with aluminum end caps. The original unexposed fuel contained 0.04 g/l of dissolved solids which was deducted to give the preceding values.

The salts which were obtained from the fuel and scraped from the specimens and dried could not be detonated by impact. This indicates that they were not azides.

8. General Conclusions from Results of Tests of Metals in MHF-3

The results thus far obtained from exposure tests and subsequent examination of coatings on Maraging steel indicate that several show promise. Coatings in the group having low rates of fuel decomposition mentioned earlier (6.2), had a satisfactorily low catalytic effect on decomposition of MHF-3 and could be considered for use in coating fuel

tanks with the exception of zinc, which was excessively corroded. The most interesting are those coatings which were least active in fuel decomposition, were least corroded, lowest in cost and the most easily applied. Of the low activity coatings thus far tested, silver was the least active, cadmium the lowest in cost and electroless nickel the most easily applied . Silver might be ruled out because of its initial cost which leaves electroless nickel and cadmium as the most practicable coatings for fuel tanks, based on results obtained to this point in the investigation.

9. Experimental Plating of Fuel Tanks

Fittings designed for plating one-half scale fuel tanks are shown in Figure 6. These Maraging steel tanks were plated through a small hole in one end. Plating solution was circulated by pump from a reservoir, through a filter and then into a hollow internal anode and thus to the bottom of the tank. Solution from the top of the tank was conducted by a return line back to the reservoir.

Two tanks were plated by this method, one each with nickel and cadmium. Several tanks were plated with electroless nickel. Similar equipment was used, but with no current supplied to the inlet tube. A hot water bath was used to maintain the near-boiling temperature necessary for plating electroless nickel.

A carbon steel, simulated full size rocket fuel tank was designed with a bolted-on end in place of the usual welded end to allow disassembly for inspection after having been plated while fully assembled. A rocker assembly was used to agitate the plating solution contained in the tank and to prevent the collection of gas in upper corners which would prevent plating or reduce plate thickness in those areas. This tank was plated with electroless nickel.

The solution was introduced and circulated through a small hole in the top. A band heater on the outside was used to maintain plating temperature. A smooth and continuous deposit about 2 mils thick was obtained on the inside of the tank. Since this tank was plated, changes made in the design include a comparatively large opening in the top of the tank so that all types of plating can be done more easily.

10. Tests of Materials Exposed to Aerozine-50

As an extension of the tests of materials exposed to MHF-3 four specimens have been exposed to Aerozine-50 (anhydrous hydrazine 50% and unsymmetrical dimethyl hydrazine 50% by volume). In contact with 18% Maraging steel, its rate of decomposition was approximately 40 times greater than that of MHF-3. However, the rates with titanium and Teflon were near zero after deducting the background rate which was about four times that for MHF-3. A sprayed coating of Teflon on aluminum gave a high rate of fuel decomposition possibly because of reaction with residual solvents or plasticizers in the coating.

11. Tests of Various Materials in Oxidizers

At the request of the sponsor, the program was extended to test the interactions between tank material and oxidizers.

11.1 Equipment for Exposing Specimens to Oxidizers

The glass units designed for fuel tests could not be used for tests involving oxidizers because of the two chosen for testing, the nitrogen tetroxide, or NTO, had a vapor pressure which was too high for practical manometer length and the hydrofluoric acid inhibitor in the inhibited red fuming nitric acid, or IRFNA, attacked the glass.(2) Therefore, it was necessary to use all stainless steel units.

In view of the high vapor pressure of the NTO at 160°F, it was decided that a bomb design like that of Figure 2 would not be sufficiently leak-proof. To run tests in this oxidizer, high-pressure bombs were purchased. These stainless steel units had a compression ring seal and compression fittings. However, it was necessary to use an additional aluminum foil gasket under the compression ring to obtain a seal that permitted no detectable leak in two weeks at a pressure of 300 psig.

The unit used with the IRFNA was similar to the unit shown in Figure 2 except that the glass liner was not used. Metal specimens in both types of bombs were insulated from metallic contact with the unit by a small Teflon cap at each end of the specimen.

An oil bath was used for maintaining the temperature of the bomb-type units. It consisted of a stainless steel tank deep enough to cover the large, high-pressure units and included a shelf for the smaller bombs containing IRFNA. As in the water baths for units containing fuel, the temperature was maintained at 160°F by a resistance heater coupled to an electronic controller.

11.2 Exposure of Various Materials to Oxidizers

The decomposition rates of NTO and IRFNA caused by contact with Maraging steel, Teflon (TFE), and 301 stainless steel (cryogenic form - aged) were relatively low, as shown in Figure 8. A unit has just been started containing a specimen of titanium. The background rate for a unit containing NTO without a specimen was 0.0417 cm^3/day.

A separate test of NTO in the form of a thin-walled tank of 301 stainless steel (cryogenic form - unaged) was run at 90°F and 10% ullage. Thus far there has been no measurable evolution of gas.

Specimens exposed to IRFNA at 160°F were Teflon (TFE), Maraging steel, Teflon-coated 6061-T6 aluminum and 301 stainless steel (cryogenic form - aged). After the first few weeks of testing, the oxidizer decomposition rate suddenly increased rapidly. It was assumed that the inhibitor, 0.7% hydrogen fluoride, had been depleted to a level that was no longer effective. After refilling the units with fresh oxidizer and inhibitor no further rapid rise in pressure has occurred.

Figure 1. Most recent design of glass test unit for measuring gas evolved from decomposition of fuel.

Features:

1. No Part of bulb assembly projects from 160°F bath, reducing condensation in upper part.
2. Cross-arm slopes toward bulb, so any condensation in this portion of bulb assembly drains back to bulb.
3. Glass frit retards diffusion to and condensation of vapor into manometer side. It also prevents accidental transfer of mercury to fuel bulb.
4. Completely sealed unit prevents leaks.
5. Initial flushing with nitrogen and periodic bleeding are accomplished through a 2 mm diameter Teflon tube inserted from the atmosphere side through the mercury column.

GLASS TEST UNIT

FOR MEASURING GAS
EVOLVED FROM
DECOMPOSITION OF FUEL

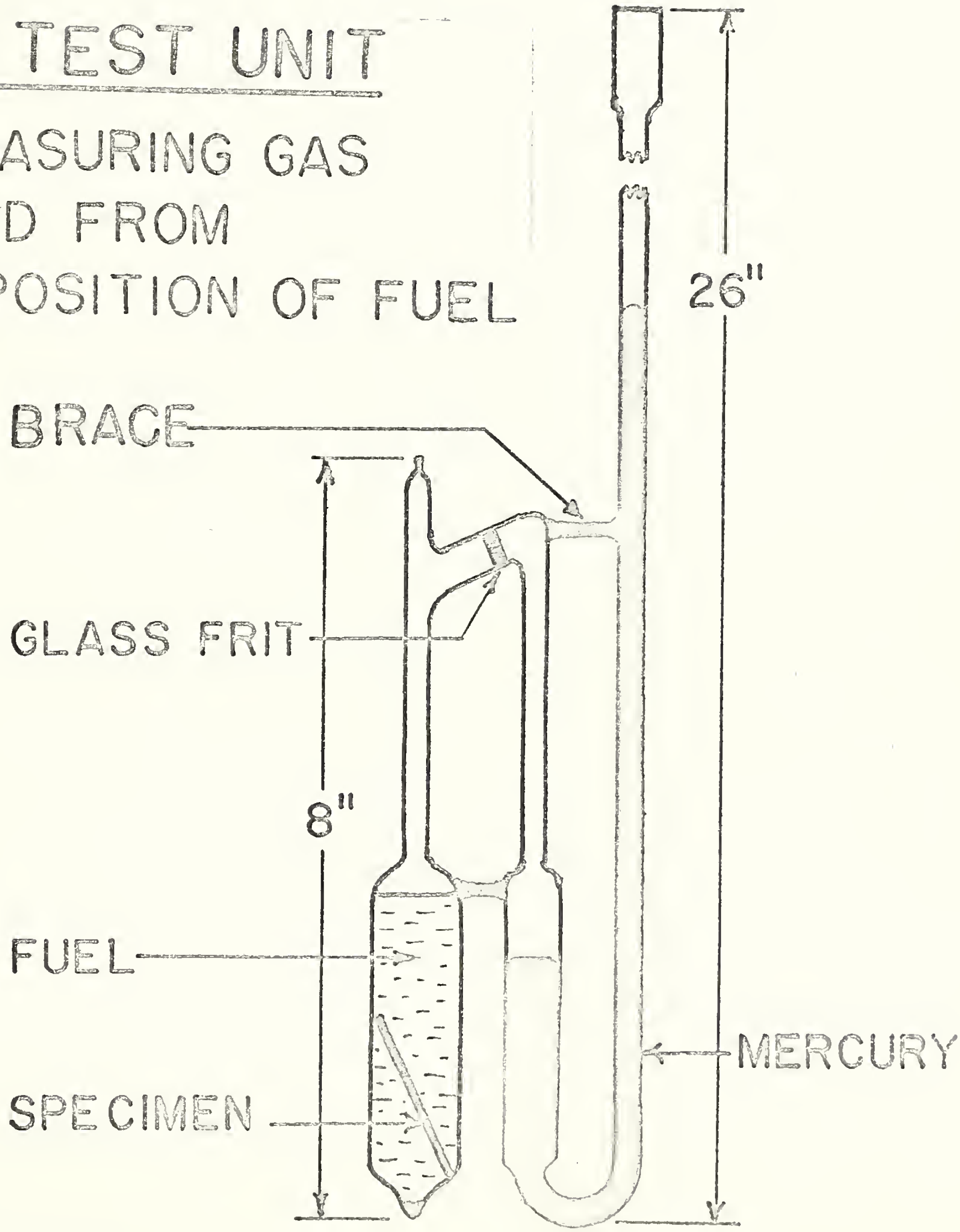


Figure 2. Metal Test Unit

A. Specimen

B. Fuel

C. Aluminum gasket

D. Pipe fittings, 1/8-inch stainless steel

E. Inlet flushing valve, stainless steel

F. Outlet flushing valve, stainless steel

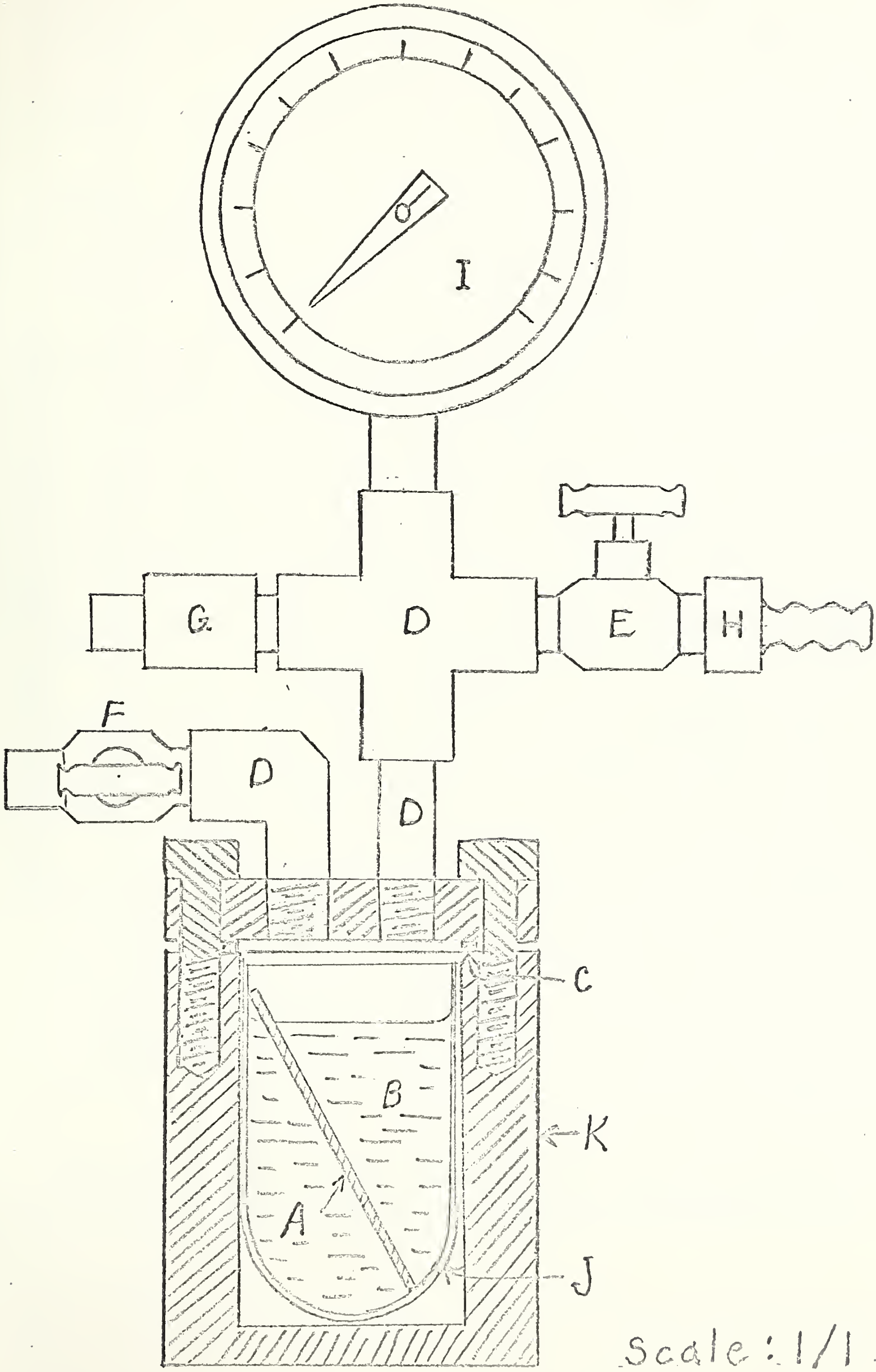
G. Safety relief valve, stainless steel

H. Hose connection, stainless steel

I. Pressure gage, stainless steel

J. Glass liner

K. Vessel, stainless steel



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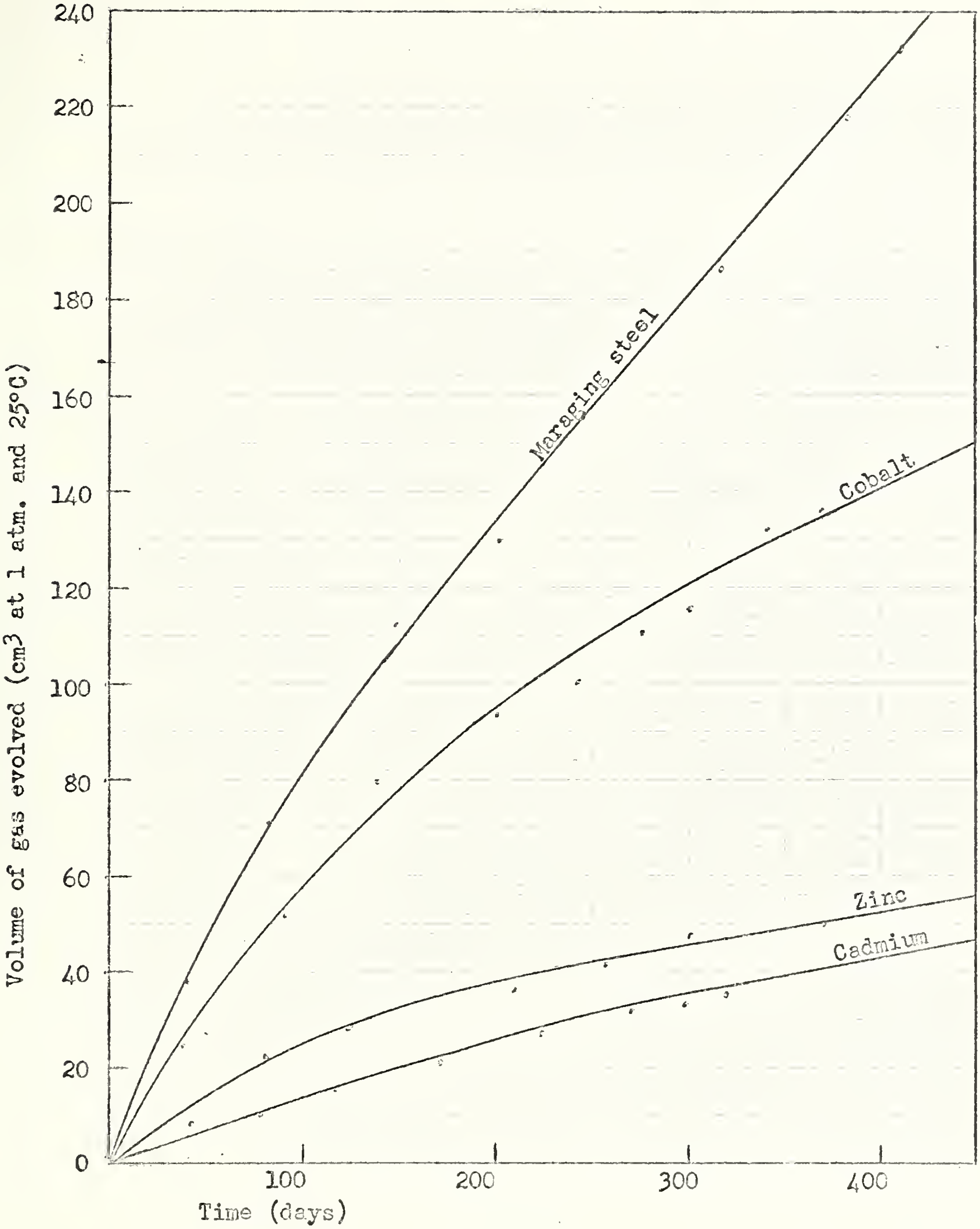


Figure 3

Rate of gas evolution from MHF-3 in contact with indicated metals at room temperature. Metal area of each specimen approximately 15 cm^2.

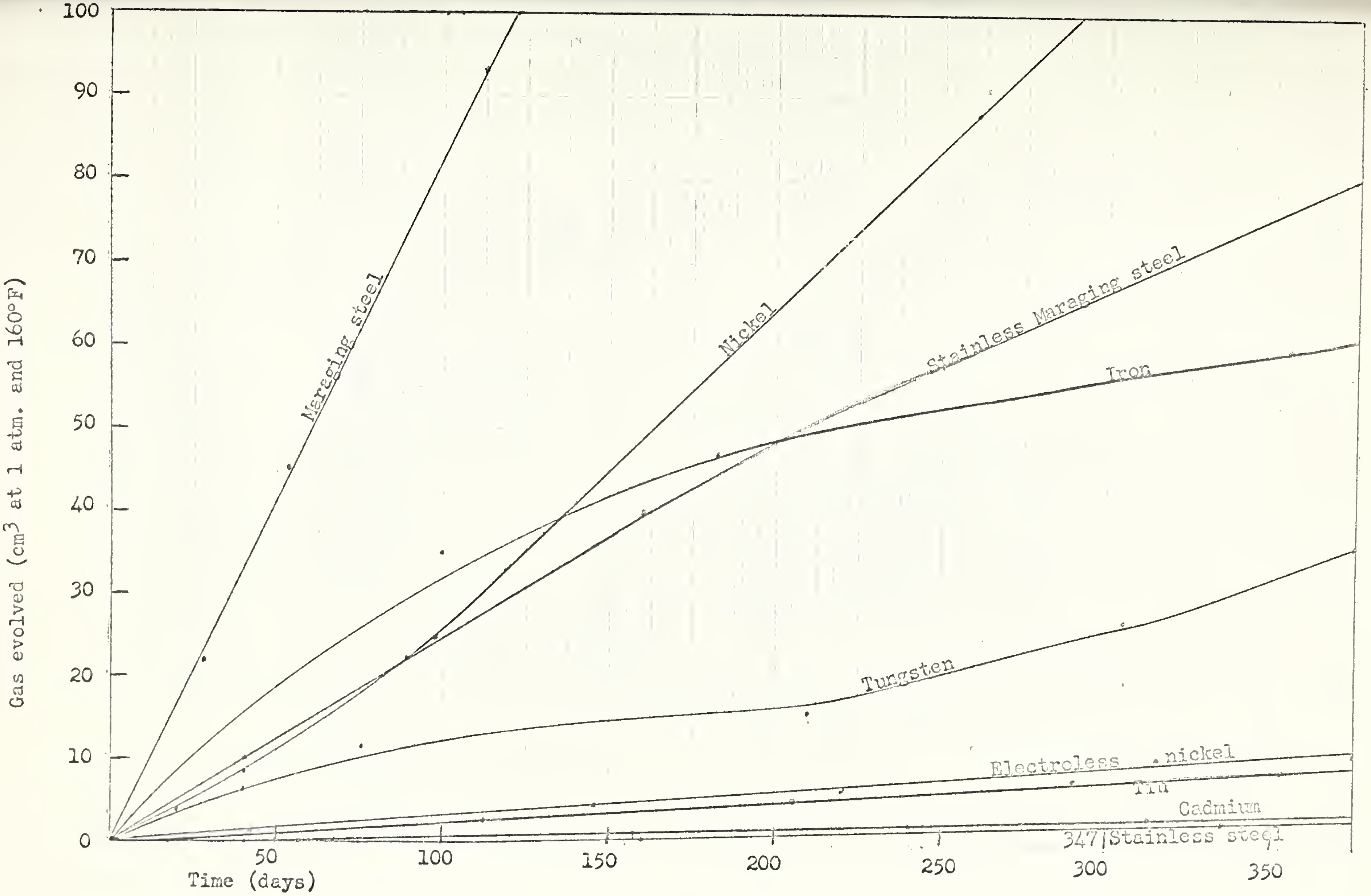


Figure 4

Rate of gas evolution from MHF-3 in contact with indicated metals at 160°F. Silver, titanium, solder and aluminum had zero or near zero rate.

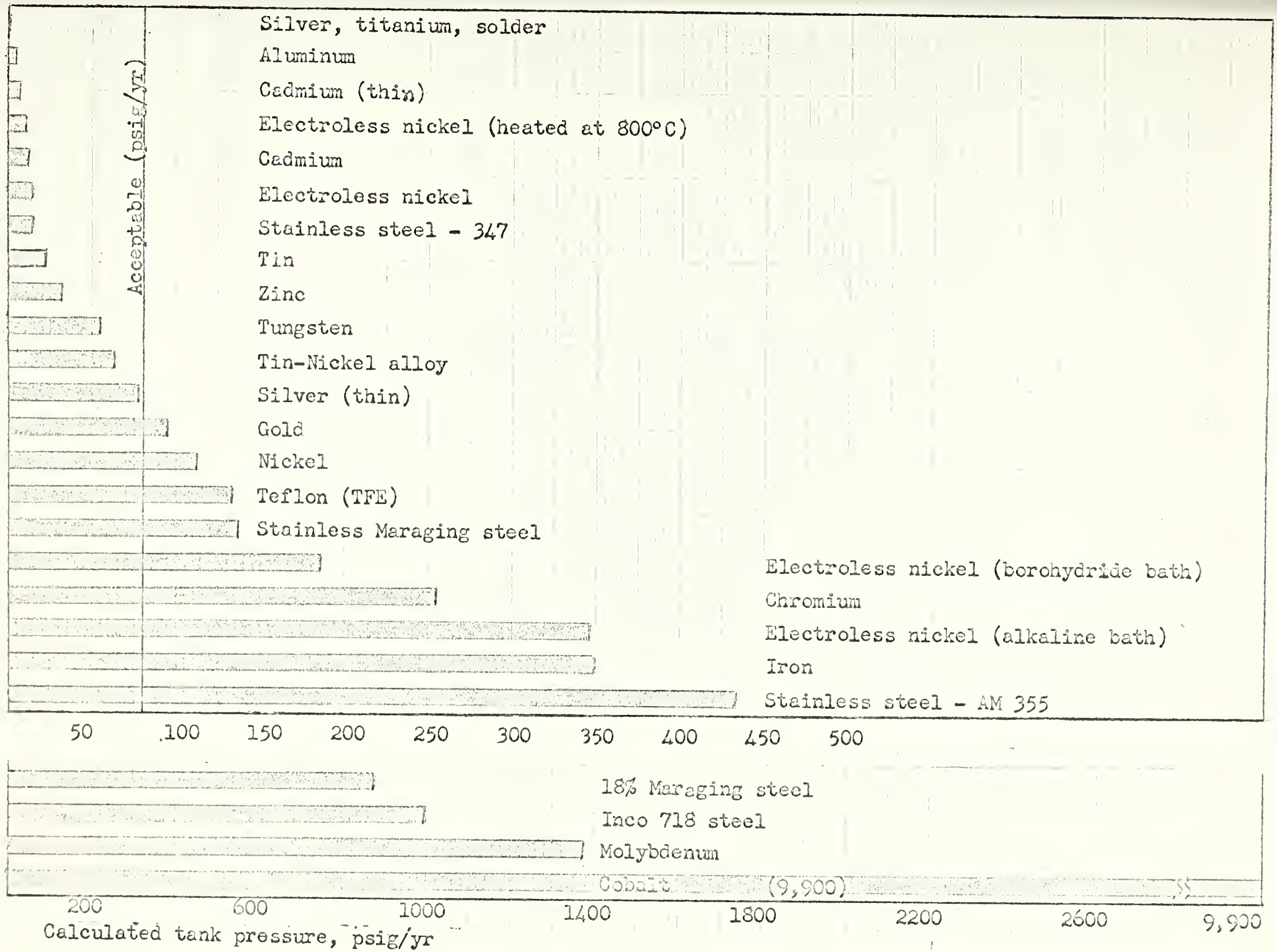


Figure 5
Gas evolution from MHF-3 in contact with indicated metals and Teflon at 160°F.

Figure 6. Arrangement for Plating Maraging Steel Cylinder

Scale: schematic view, 1" = 4"
detail of head, 1" = 1"

Arrows show flow of plating solution.

A. Cylinder

B. Combination anode and inlet tube for plating solution

C. Plating solution in reservoir tank

D. Pump

E. Filter

F. Detail of inlet tube, 5/16" o.d., 1/4" i.d., stainless steel

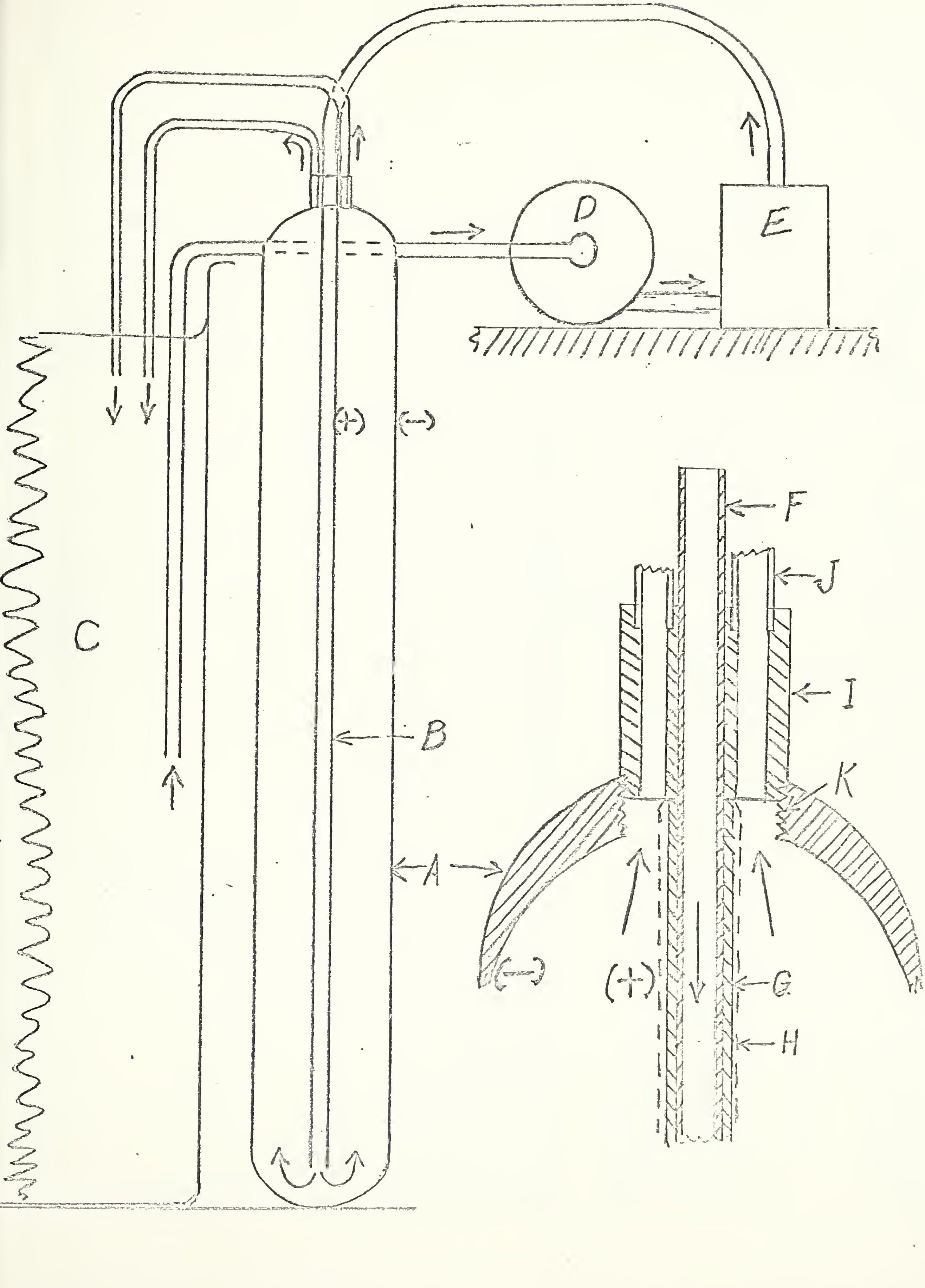
G. Nickel plate on inlet tube, 1/16" thick

H. Fabric bag surrounding anode

I. PVC plug

J. PVC tubing for plating solution exit

K. Taper pipe thread, 3/4" NPT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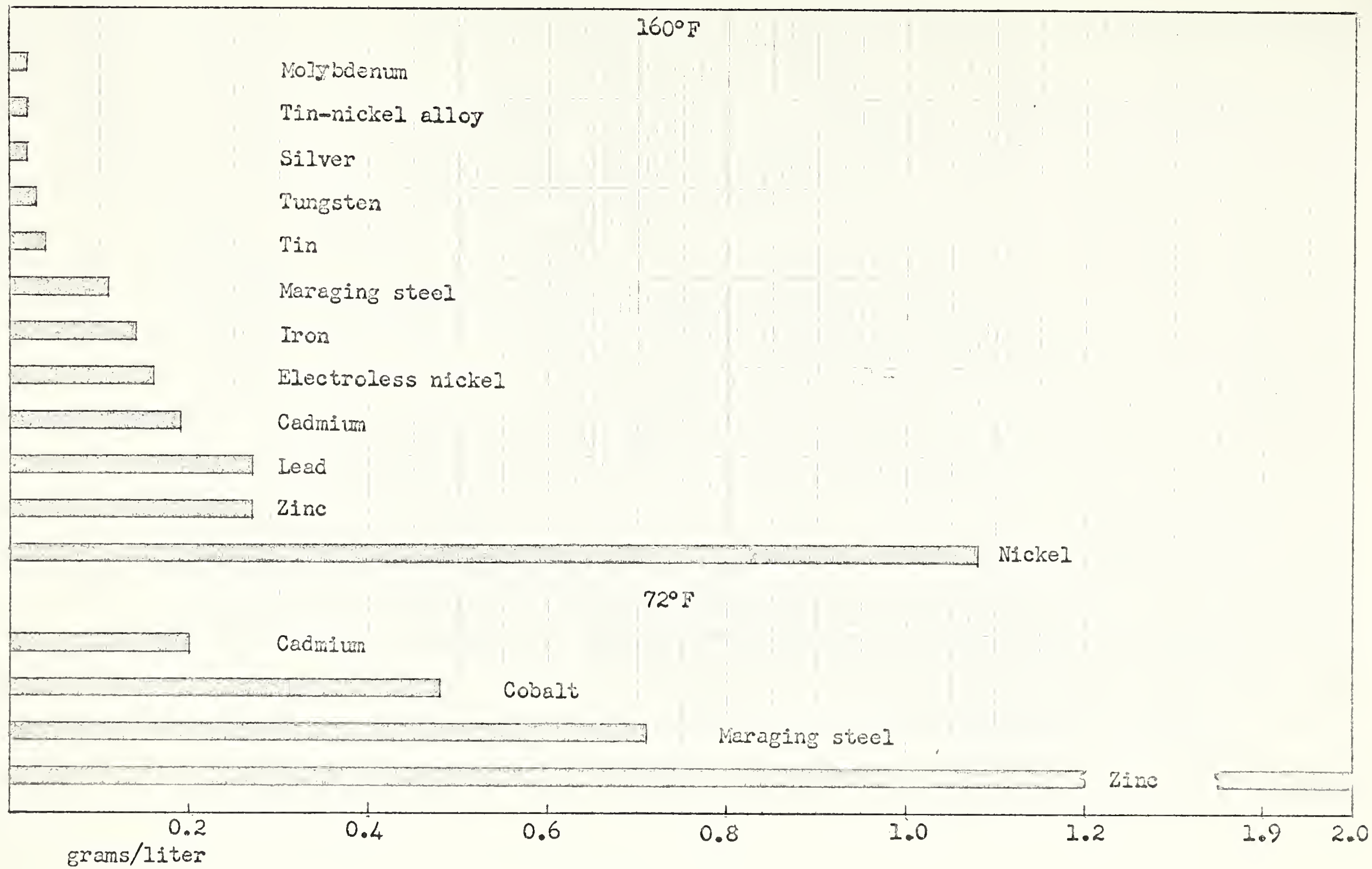

Figure 7

Concentration of dissolved salts in MHF-3 fuel from test units as determined by evaporation. Deducted is 0.04 g/l solids in unexposed fuel. Dissolved metal salts are not necessarily proportional to amount of corrosion as usually some precipitate was formed. The generally lower concentrations at 160°F are explained by formation of a greater amount of precipitate or a protective oxide.

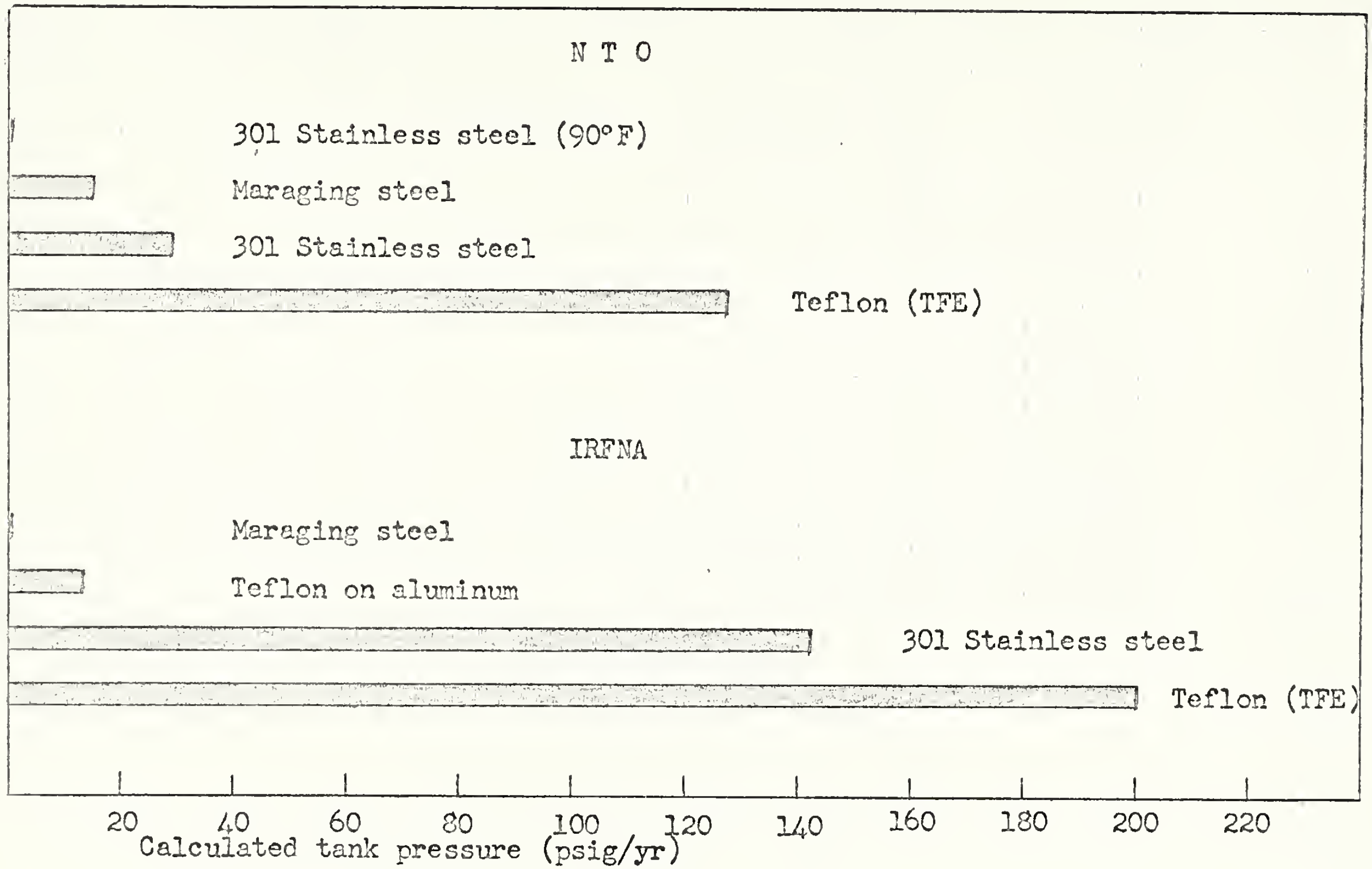

Figure 8

Gas evolution as indicated by pressure increase resulting from contact of above materials with NTO and IRFNA at 160°F for four months.


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