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ELECTROSTATIC CHARGING TEST FOR AVIATION FUEL FILTERS

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ELECTROSTATIC CHARGING TEST FOR AVIATION FUEL FILTERS

(CRC PROJECT NO. CA-48-71)

Prepared by the

Field Test Panel

of the

Aviation Group on Filter Charging Characteristics

November 1983

Aviation Fuel, Lubricant, and Equipment Research Committee

of the

Coordinating Research Council, Inc.

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CHAPTER 1

EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

In response to two low-order static ignitions in aircraft in 1970, the Coordinating Research Council (CRC) renewed their research into the electrostatic hazards in aircraft fueling at the request of the Federal Aviation Administration. A summary of the initial investigations of fuels, ground filtration equipment, and filter elements was presented to the 1975 Conference on Lightning and Static Electricity(1). The individual CRC reports on static in fueling(2-5) revealed that certain fuels, some types of filter elements, and environmental factors such as temperature and fuel water content had pronounced pro-static charging tendencies.

As a result of these findings, it was proposed by the Federal Aviation Administration (FAA) that a CRC research technique be developed for measuring the charging tendency of individual filter elements under controlled conditions and that the usefulness of the technique be verified by appropriate field tests. Such a research technique would be useful toward the design and qualification of filter material with minimum electrostatic charging hazard. Under CRC contract, Exxon Research and Engineering Company developed a rig procedure as a Filter Charging Test(5) for full-scale individual filter elements, both coalescers and water separators.

To verify the rig procedure, CRC formed a Field Test Panel which, over a period of two years (1976 and 1977), conducted controlled tests on electrostatic charging of fifteen hydrant carts containing various filter elements. These tests were conducted at Chicago's O'Hare International Airport with the cooperation of the Lockheed Air Terminal (LAT) Company, fueling agents for the airlines. Three different fuel systems were tested using assigned carts of similar design. At the end of the last test period, elements from two of the carts were sent to Exxon Research where CRC Filter Charging Tests were carried out. Chapters 2 and 3 of this report detail the results of both the field tests and the verification tests carried out in the CRC rig.

A major finding of both field and rig tests was the relatively high charging tendency of coalescers, the first stage of a two-stage filter separator system, which in some cases contributed significantly to the static charge in fuel delivered to aircraft. On the other hand, in none of the field tests did the overall charging level reach a level considered hazardous to aircraft based on earlier experience.

A second major result of these two test programs was the generally good verification of the field tests using the CRC Filter Charging Rig. Separator elements (SP-1 and SP-10) of one manufacturer (all filter elements are coded in this report) were ranked as more active than the other manufacturer's elements (SP-2) in both new and used condition in both rig and field tests. An increase in temperature raised charge output (negatively) in both rig and field tests. Used coalescer elements (CF-1) from field tests were up to sixteen times higher in charging tendency than separator elements in rig tests; similar results were derived from analysis of field tests. Laboratory tests of the three field test fuels showed the same ranking in charging tendency as was observed in the field tests. While the Filter Charging Rig used a different test fuel than the three LAT fuels, it proved to have similar charging tendency to the most active of the field test fuels (also coded in this report). The only variable that was not possible to verify in rig tests was the effect of fuel water content which, unfortunately, was not measured in the field.

Charging tendency in the field was measured in a special simulated aircraft inlet manifold developed by Boeing which contained two receivers for hose end nozzles and an A. O. Smith Charge Density Meter. The manifold was mounted on a truck and taken to three different fuel hydrant system filling racks on the airport. Each test hydrant cart containing a horizontal filter/separator was brought to the rack from which it pumped fuel from one satellite tank at two different flow rates through the simulated manifold into a separate satellite tank. Temperatures and flow rates were measured and signals from the charge density meter were monitored with a Keithley electrometer and continuously recorded. About twelve hydrant cart tests could be conducted in one day. Four test periods (October 1976 to August 1977) provided a range of fuel temperatures from 30°F to 76°F.

The rest conductivity of the three test fuels (coded A, B, and C) could not be measured with the field instrument available (designed for fuels containing anti-static additives), because each fuel had been refined and contained no conductivity-improving additive. Instead, the charge decay curve after flow stopped was observed on the recorder charts, and the "effective" conductivity of fuel was calculated by observing the time for 50 percent of the charge to relax using the widely recognized equation:

$$QF = Qi\ e^{\frac{-Kt}{\varepsilon\ \varepsilon_0}}$$

where: QF = residual charge after time t

Qi = initial charge at time zero

K = effective conductivity in pS/m

t = residence time in seconds

ε = dielectric permittivity of hydrocarbon, about 2 pF/m

ε_0 = dielectric permittivity of free space, 8.84 pF/m

A conductivity of fuel determined by observing time for relaxation is different than a conductivity determined by inserting a fuel sample into a test cell as in ASTM D 3114, but is probably closer to the conductivity exhibited by flowing fuel through vessels such as filter/separator cases. Much of the data analysis depended upon calculated fuel conductivities and the determination as to whether ohmic or hyperbolic charge decay prevailed.

Analysis of the variables explored in the field test program revealed that fuel quality (in terms of charging tendency) was very important. For example, only Fuel A, the most active fuel, showed an increase in charging tendency as temperature increased from 30 to 53°F. At the highest test temperature, 75°F, all fuels showed greater charge output, but Fuel A remained the most active. These fuel effects masked any effect of total throughput accumulated on filter media in individual carts.

The variable of flow rate produced a consistent pattern of decreased charge density as the rate was raised from 40 percent to 100 percent of rated flow.

Since the charge output measured in these field tests represented the algebraic sum of the charging contributions of both coalescer and separator elements, it was recognized that special tests would be needed to separate the effects of individual filter elements. The opportunity to perform special tests arose in the last (August 1977) test series. Two methods of analysis resulted. In the first method, the coalescers were simply removed from certain carts so that separators only were tested and compared on the same fuel. One test was then performed without separators and another with a screen separator to examine coalescers separately. A second method of analysis suggested itself when it was observed that the recorder traces exhibited two charging peaks after flow started: the first representing the separator alone; the second peak, many seconds later, representing the combined effect of coalescer and separator. Thus, it was possible to back-calculate coalescer effects.

It was found that the charging levels of coalescers were frequently higher than the separators, and that the average level was related to fuel quality. Fuel C, the least active fuel, exhibited low charge with both types of elements; Fuel A, the most active fuel, the highest charge with both elements; while Fuel B was intermediate in both activity and element charging level. In about half the cases, the polarity of charge produced by the coalescer was the same as the separator, so that the output of the first stage reinforced the second stage. On the other hand, except when running special tests without separators, Fuel A, unlike the other fuels, always produced positive charge from the coalescers and negative charge from the separators.

The critical importance of a controlled and uniform fuel supply for each test series was dramatically illustrated by the results with Fuel A in the last test period. While testing the carts assigned to Fuel A, it was observed that charging levels were erratic and reversed polarity several times during a run. This was traced to a failure by the operators to isolate the feedtank so that fuel of obviously different charging tendency was entering the feedtank during test. Once the tank was properly isolated, a uniform Fuel A was available for testing. It was this well-controlled Fuel A source that was used for special cart testing with coalescers removed.

The results of special tests without coalescer elements unambiguously confirmed other test results that Separator SP-1 produced negative charging levels twice as high as Separator SP-2. The test of a screen-type separator showed it to be negligible in charging characteristics. When the data were analyzed to calculate the coalescer element's charging tendency with the same fuel, a positive charging tendency of two to five times higher than Separator SP-2 was determined for one test cart. The coalescer associated with Separator SP-1, however, charged negatively at a level somewhat lower than the separator.

The used coalescers and Separators SP-1 and SP-2 last tested with Fuel A in Carts E-332 and E-338 were then removed and sent to Exxon Research and Engineering Company for verification tests in the CRC Filter Charging Rig. At the same time, samples of Fuels A, B, and C from the airport hydrant systems were also sent to Exxon for testing and comparison with the test fuel used in the Filter Charging Rig.

Small-scale laboratory tests of charging tendency of fuels using the MiniStatic Test (MST)(4) were made using various filter media, including the paper separators of both manufacturers. Rig Fuel D proved to be closest to Fuel A in MST tests and in rest conductivity. Fuel C was the least active in charging tendency. With all four fuels, the Separator SP-1 paper was consistently several times higher in charging tendency than Separator SP-2 paper. These fuel and filter media rankings corresponded closely to the field observations and substantiated the MST test as a small-scale laboratory evaluation tool, and the use of Exxon test fuel as an appropriate reference fuel for full-scale rig testing.

The CRC Filter Charging Rig procedure involves the flow of test fuel simultaneously through two parallel test vessels at identical flow rates to compare a test element with a reference element. The test fuel enters the test sections either charged or uncharged by elements such as coalescers mounted in precharging vessels. Moreover, the charging data are collected under three different fuel temperature and fuel water content levels. Because of these various permutations, 146 runs were carried out to evaluate both new and used elements from airport field tests.

Testing of both new and used elements in the Filter Charging Rig confirmed field data that Separator SP-1 charged at a three-fold higher level than Separator SP-2, the difference increasing as temperature increased. Used coalescers from the carts associated with these separators charged at considerably higher levels than the separators, and also showed an increased charge with increased temperature. There was no significant difference between used coalescers in rig tests, although field data suggested that the two carts' coalescers charged with opposite polarity.

The rig's finding that coalescers exhibited such high charging tendency coupled with the analysis of field data from recorded peak values made it clear that first-stage elements of filter-separators contributed significantly to the total output of these units, especially with active fuels of low conductivity. In turn, this suggested the desirability of utilizing the CRC Filter Charging Rig as a screening tool for full-scale coalescers elements, as well as for separators. It also led to the recommendation that a small-scale laboratory test for coalescers similar to the MST test for separators should be developed.

The overall comparison of rig and field data summarized in Table 1-1 shows that on almost all counts, filter charging rig data on filter elements were verified by actual field observations. The CRC rig is thus demonstrated to be a useful research technique for evaluation of either new or used filters for application to ground fueling systems when low-conductivity fuels are delivered to aircraft.

TABLE 1-1

SUMMARY OF VERIFICATION OF LABORATORY TESTS BY FIELD RESULTS ON STATIC CHARGING OF FILTER ELEMENTS

TESTS ON FUELS	Laboratory Tests	Field Results
Conductivity	K_r	K_e
A	2	0.69
B	0.93	0.24
C	0.98	0.11
Rig	1.5	---
Charging Tendency-Overall CD Activity		
A	Intermediate	Most
B	Most	Intermediate
C	Least	Least
Rig	Intermediate	---
TESTS ON FILTER MEDIA		
Separators: - New		
MST: SP-1/SP-2	3 - 5	
RIG: SP-1/SP-2 Ratio of CD	2.5	
Field: SP-1/SP-2 Ratio of CD		9
Separators: Used		
MST: SP-1/SP-2 Ratio of CD	1.3	
RIG: SP-1/SP-2 Ratio of CD	3 - 4	
Field: SP-1/SP-2 Ratio of CD		2
Coalescers: Used		
RIG: CD	270	
Field: CD		107 - 254
Combined Coalescers + Separators - Effect on Output CD		
RIG:	Significant	
Field:		Significant

Notes: Fuels are coded A, B, and C
Separators are coded SP-1 and SP-2
CD = Charge Density in $\mu C/m^3$
K_r = rest conductivity pS/m
K_e = effective conductivity pS/m

CHAPTER 2

FIELD TEST REPORT

FIELD TEST REPORT

A. Objective and Scope

The objective of the field test program was the measurement of filter charging levels in actual aircraft fueling (hydrant cart) equipment to provide correlation data for the laboratory charging test program. The field test location and equipment were selected to provide a high total fuel throughput under typical refueling conditions. The designated hydrant carts were equipped with new separator elements supplied from specific batches by two major manufacturers. Periodic electrostatic charging measurements were conducted over a range of typical refueling conditions, which could be approximated in the laboratory program. New and used filter elements from the selected batches and representative fuel samples were provided to the laboratory program for correlative measurements.

B. Facility

A requirement for high throughput fueling equipment limited the facility selection to major airports and to hydrant systems. The further requirement of five to ten individual test systems, representing the combinations of several fuel sources and two separator types, necessitated a location with a large number of identical fueling vehicles which would be available for repeat tests during a period of at least one year. Finally, the need for adequate test stands and equipment narrowed the selection to the Lockheed Air Terminal (LAT) facilities at Chicago's O'Hare Field. This facility was used in earlier fuel charging studies, and LAT generously offered the use of their facility and their assistance to the Field Test Panel. The O'Hare Airport Fuel Committee also provided support for this program.

A typical LAT hydrant cart is shown in Figure 2-1. The carts are equipped with a 700-gpm Fram horizontal filter/separator (F/S) (Model FCS-1361-22N1) holding thirteen 16-1/4" x 6" separator elements and twenty-two 14-1/2" coalescer elements. The elements are accessible through a flanged manhole on the upper surface. The piping arrangement for a typical LAT hydrant cart is shown in Figure 2-2. The approximate fuel volume and displacement time for each section of the cart is shown in Appendix B.

Hose connections were provided at the LAT prover loop (handling Fuel A) and at two satellite facilities (handling Fuels B and C) allowing measurements at each system, adjacent to the aircraft fueling positions. The test connections permitted rated fuel flow through the selected hydrant cart, the instrument system, and return to a separate underground satellite tank.

Fifteen similar hydrant carts were initially designated for the test program. Five carts normally operated with each of the three designated fuel sources were inspected and changed to the test separator elements. Three primary carts (one with each separator type plus one containing a mixture of the two separators) were used in further testing with each fuel type (Table 2-1), with the remaining two units (one with each separator type) maintained as spare test units. The primary test units were intentionally scheduled to handle larger fuel volumes during the one-year test period. Tests were scheduled with the subject units at three-month intervals, thereby providing data at various fuel temperatures and separator element throughput. The initial and third measurements were scheduled to use fuel at approximately 55°F. The second and last test sequence used fuel at temperatures approximately 20°F below and above this level, respectively, thereby providing a significant spread in fueling temperatures.

C. Test Fuel

Three commercial Jet A fuels, supplied in volume at O'Hare Field, were used throughout the field test program. The test hydrant carts were assigned to a particular fuel source and operated almost exclusively on that fuel during normal operation and the test sequences. The individual test fuels were generally supplied from single refinery sources; hence, they were fairly consistent in characteristics during the test period. The test fuels represented different crude sources, refinery processing, and airport treating techniques, as indicated in Table 2-2. No further attempt was made to control test fuel quality.

Visual examination showed the test fuels to be "clear and bright" at all times. Field measurements of total water content were attempted, but were not successful due to difficulties in calibrating the precision equipment under field conditions. Random measurements of field conductivity using a portable meter showed values under 2-3 pS/m, the limit of the equipment. Effective conductivity was thus calculated using charge relaxation measurements as described subsequently. The effective conductivity was highest for Fuel A, which was not clay-filtered. In the last test period, Fuel B increased in charging activity, perhaps because the clay filtration facility was approaching the end of its useful life and was not removing the ionic species that contribute to conductivity or to charging tendency.

D. Test Elements

The separator elements were assumed to be a prime contributor to electrostatic charging in a F/A system. Accordingly, two widely used elements manufactured by major US suppliers were selected for use in the field and laboratory test programs. A large batch of each element type was isolated for use in these programs and any related program at other locations. The separator elements represent different material sources and possibly different assembly and treating practices. Preliminary data indicated significant differences in electrostatic charging characteristics between these elements.

The existing coalescer elements were retained in the test carts; however, the elements were primarily of one type, and had limited usage with the same fuel sources, before this program (Table 2-3).

Selected used elements from this program were included in subsequent evaluations in the laboratory program to provide further correlation.

E. Measurement System

Electrostatic charging in the hydrant cart piping and filtration system was measured by a downstream static charge density meter(1) in a prefabricated in-line manifold (Figures 2-3 and 2-4). Signals were monitored with a Keithley Model 600B electrometer and recorded with an Esterline Angus 0-1 ma portable strip-chart recorder. A constant chart speed of 1.5 inches/minute provided time reference for the test sequences. A typical test record is shown in Figure 2-5. This same equipment was used in a previously reported program conducted at this same facility. From the recorder charts of electrometer output, charge densities at different times were calculated and became the basis of subsequent analysis.

The in-line manifold which simulated the receiving parts of an aircraft fuel system was carried on a truck to each test location. There, it received fuel through the dual hoses from each hydrant cart, and delivered fuel from its hoses into an underground receiving tank.

F. Field Test Program

The field test program was designed to examine the charging characteristics of separator elements from different sources under conditions which would include the following variables:

- Fuel quality; e.g., source and conductivity
- Fuel temperature
- Flow rate through elements
- Separator throughput

It was planned to make charge density measurements with each of the test carts at different times throughout the year, which would represent different fuel temperatures and element throughputs. The same fuels and carts tested at two different flow rates; maximum (600 gpm) and 40 percent of rated flow (250 gpm) would provide the other variables.

1. Initial Testing: October 1976

Test Separators SP-1 and SP-2 were installed in three hydrant carts assigned to Fuel A on October 27, 1976. Details of all test-cart separator installations are shown in Table 2-4 which indicates the throughput of each cart from October 1976 to this final test period of August 1977. Initial testing with Fuel A took place on October 28 at maximum flow rates. Equilibrium charge density measurements are shown in Table 2-5. Operation continued until about thirty thousand gallons had been flowed in order to examine the "break-in" characteristics of these new separator elements. In each case, the charge density decayed gradually with time. Marked differences in charge output were noted between Separators SP-1 and SP-2. The cart with mixed elements gave results between the data for the two carts with dedicated separators.

2. Test Period B: February 1977

All carts were tested with the three test fuels in February when the average fuel temperature was near 30°F. From the recording traces, it was observed that upon start-up one or two peak charge density values could be detected before the output reached equilibrium. In Table 2-6, the peak and final values, as well as the time intervals for peak values, are summarized at two different flow rates. In some cases, repeat tests were made. All charging levels were low mainly due to the low temperatures of the fuel. Differences between separators were noted mainly in the peak values.

3. Test Period C: May 1977

All carts were again tested with the three test fuels on May 3 when the average fuel temperature was about 55°F. Once again, one or two peak charge values were detected upon start-up. In Table 2-7, these peak values and time intervals plus equilibrium values are summarized at two different flow rates. In addition, the time for 50 percent of the charge to relax upon flow shutoff is shown. Fuel A proved to be considerably more active than Fuels B or C. Significant differences were now observed between Separators SP-1 and SP-2.

Repeat tests the following day (May 4) with Fuel A confirmed its high activity; the greater conductivity of Fuel A was detected by its shorter relaxation time. A test with a cart containing a permanent-type (Teflon-coated) screen instead of a separator showed higher than expected peak values, presumably due to the coalescer's charge contribution, and suggested the need for separate testing of individual elements.

4. Test Period D: August 1977

The final test sequence occurred on August 3 when the fuel temperature had reached about 75°F. Testing with Fuel A provided wide and unaccountable variations in charge level. In most cases, the equilibrium charge value would reverse polarity several times during a run. The problem was traced to an open connection between the supply and return tanks which allowed charged fuel to enter the supply inlet. After isolating Supply Tank 207, tests were repeated with Cart E-332; the same isolated tank provided the feed for the testing on August 4.

Fuel B proved to be considerably more active than Fuel C, and differences between Separators SP-1 and SP-2 were significant. Table 2-8 provides a summary of the data on peak and final charge values, time intervals for peaks, and observations of 50 percent decay time.

On August 4, the coalescers were removed from Carts E-332 and E-338 in order to test Separators SP-2 and SP-1, respectively, without influence from the first-stage coalescer (Table 2-8). Cart E-303 with its permanent-type separator was also tested and, as final measurement, the coalescers were returned to Cart E-332 and the separators were removed in order to provide one test of first-stage coalescer units alone.

After these tests were terminated, representative used separator and coalescer elements were removed from the six test vehicles equipped with specific types and forwarded to the contract laboratory for evaluation in the laboratory rig.

G. Data Analysis

1. Separate Role of Coalescer and Separator Elements

The charge density recordings in Figure 2-5 illustrate a number of interesting charging events. Thirteen seconds after flow started, a peak negative charge was recorded. Twenty seconds after that event, a second and higher negative charge was noted, after which the charge declined to a steady state. The first peak clearly represents the charge in fuel produced by the separators alone, while the second peak indicates the combined effect of charges produced by coalescers and separators in the fuel reaching the charge density meter (CDM). When data like these on peak charge densities and time are combined with information on fuel conductivity, it is possible to calculate the separate contributions to fuel charge of separator and coalescers at the source; i.e., at the sets of elements. The separate contributions may represent opposite polarities, in which case charges would cancel each other rather than add. The technique for making these calculations from CDM readings is developed in Appendix B.

Resulting peak charging calculations for three test periods are summarized in Table 2-9. CDM readings at the same maximum flow rate extracted from Tables 2-6, 2-7, and 2-8 were used to permit comparisons among different filter elements. As discussed in Appendix B, the calculation technique can involve either exponential charge decay (constant conductivity) or hyperbolic charge decay (constant ion mobility), the latter phenomenon generally prevailing when fuels exhibit a rest conductivity well below one pS/m. The following comments apply to Table 2-9:

- For Test Period B when fuel temperatures and conductivities were low, it was assumed that charge output of the elements decayed hyperbolically with an ion mobility of 0.3×10^{-8} m^2/v-s. Fuel A was a much more active charger than Fuels B and C with both separators and coalescers. Separator SP-1 showed greater charging activity than Separator SP-2 with Fuels A and B. Coalescer charging with Fuel A was opposite (positive) in polarity compared with separators.

- For Test Period C when fuel temperatures were higher, effective conductivities were calculated at 0.54 pS/m for Fuel A, much lower for the others. It was assumed that charge decayed ohmically with Fuel A, and hyperbolically with Fuels B and C with an ion mobility of 10^{-8} m^2/v-s. As before, Fuel A displayed much more charging activity than Fuels B and C, and Separator SP-1 more activity than Separator SP-2. A permanent separator shows no charging activity. Repeat tests with Fuel A suggested that fuel quality was varying from run to run. Coalescer charging varied from -84 to +293 $\mu C/m^3$ in charge output.

- For Test Period D, fuel temperatures and conductivities were highest. For Fuels A and B, effective conductivities of 0.69 pS/m and 0.54 pS/m, respectively, were used in ohmic decay calculations, but for Fuel C hyperbolic charge decay was assumed as in the previous test period. Both Fuels A and B appeared to be active chargers compared with Fuels C and as before, Separator SP-1 exhibited greater charging activity than Separator SP-2. Fuel A seemed to vary from run to run. Coalescer charging equalled or exceeded separator charging over a range of -125 to +400 $\mu C/m^3$.

The second day of testing in Test Period D with Fuel A of uniform quality (as a result of isolating the supply tank) was the opportunity to test separator and coalescer elements separately. The data from Table 2-8 have been analyzed using the appendix B procedure with results summarized in Table 2-10. The ohmic decay curve of Fuel A at an effective conductivity of 0.69 pS/m was used for these calculations. The following comments apply to Table 2-10:

- In the absence of coalescer elements, Separator SP-1 shows a significantly higher equilibrium charging level than Separator SP-2. Peak charging levels were also higher with Separator SP-1.
- It is significant to note that a permanent-type screen separator shows essentially no charging activity on either a peak or equilibrium basis, although a second peak in the recorder demonstrates clearly the contribution of the coalescer.
- The single test of coalescer elements only with Cart E-338 produced a moderate charging level (over 100 $\mu C/m^3$) on a peak basis and more modest values at equilibrium. All values were negative in polarity like the separators.
- An indirect measure of coalescer elements in Cart E-332 was made by combining the results of two tests. By subtracting the charge contribution of Separator SP-2 from the charge of combined elements, a high coalescer charge (over 250 $\mu C/m^3$) of positive polarity was calculated.

2. Effect of Fuel Temperature on Charging Tendency

The four test periods which covered a period of almost a year represented a range of fuel temperature from 30 to 75°F. The equilibrium charge densities for carts representing Separators SP-1, SP-2, and their mixture are plotted against temperature in Figures 2-6 to 2-8 for maximum flow rates. Although there is a net increase in charge level with temperature under all conditions, the levels with Fuels B and C are generally too low to show significant change. With the more active Fuel A, the increase of charging tendency with temperature is more pronounced.

3. Effect of Total Fuel Throughput on Cart Charging Tendency

The four test periods also represent successively greater total fuel throughput as indicated in Table 2-4. Even though throughput varied by a factor of two among test carts, there was no consistent relation to measured charging tendency.

4. Effect of Fuel Quality on Cart Charging Tendency

Test fuels were consistently supplied to the airport hydrant systems from the same refineries during the year-long period. With Fuel C, charge densities were consistently low compared with the more active Fuel A. Fuel B charged at an intermediate level, closer to Fuel C, except at the last test period. It is evident that fuel quality is a major factor in field results.

H. Discussion

The importance of the contribution of the first-stage coalescer to the overall cart charging tendency was not appreciated until the third test period. Even so, the field attempts to quantify the coalescer's contribution were not carried out until the last day of the final test period. Nevertheless, the indirect evidence from the recorded charging peaks in each test period did suggest that coalescer charging covered as wide a range as separator charging, up to 400 $\mu C/m^3$. Verification by direct measurement of coalescer charging in the final test day showed only -107 $\mu C/m^3$, while tests with one cart produced a coalescer estimate of +254 $\mu C/m^3$ by subtracting the measured separator effect from the combined effect. The evidence is therefore very strong that coalescer charging is a significant factor in cart charging tests, especially with low-conductivity fuels.

Despite the uncertainties of measurement with both elements in place, the field data clearly showed that Separator SP-1 was considerably more active than Separator SP-2 under almost all fuel and temperature conditions. The carts with a mixture of separator types always gave charge levels that fell between the two carts with dedicated separators.

The best way to quantify the comparison of separators was to utilize the peak charging values calculated in Tables 2-9 and 2-10. The ratios of charge densities of Separator SP-1/SP-2 are summarized in Table 2-11. The highest rates were realized with the most active fuel. Special tests using Fuel A with separator elements alone promised the most unambiguous comparison; on average, Separator SP-1 showed twice the charging activity of Separator SP-2.

Fuel quality was demonstrated to be as important as filter type in charge output. The most highly refined fuel not only exhibited the lowest conductivity but was the least active in charging tendency. Fuel A, which was not clay-filtered, was the highest in conductivity and the most active in charging tendency. The uniformity of these general qualities of fuels over a year-long test period was surprising. The importance of this uniformity in obtaining meaningful test data was illustrated by the problems with Fuel A in the last test series when the supply tank was not isolated from the rundown of charged fuel. It is regrettable that neither fuel conductivity nor water content could be measured directly in the field, as it is obvious that both factors are important in charge relaxation and charge generation respectively.

TABLE 2-1

LAT TEST UNITS

LAT Vehicle No.	Test Fuel	Test Separators(1)	Test Separators Installed	Coalescer Type	Coalescer Installed	Equipped With Hydraulic Lift
E-332	A	SP-2	10/27/76	CF-1	12/01/76	Yes
E-338	A	SP-1	10/27/76	CF-1	11/20/75	Yes
E-333	A	SP-1 & 2	10/27/76	CF-1	02/01/76	Yes
E-348	B	SP-2	12/07/76	CF-2	12/08/74	No
E-313	B	SP-1	-	CF-1	02/16/76	Yes
E-326	B	SP-1 & 2	12/06/76	CF-2	02/18/76	No
E-304	C	SP-2	12/27/76	CF-1	07/21/75	Yes
E-308	C	SP-1	12/13/76	CF-1	07/20/75	No
E-323	C	SP-1 & 2	12/28/76	CF-1	11/19/75	Yes
E-303	A	ST				No

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(1) Separator Type SP-1 & 2 = Mixture of Separator Types SP-1 and SP-2.

TABLE 2-2

O'HARE TEST FUELS

Fuel Supplier	A	B	C
Crude Source			Mixed Domestic and Foreign
Refinery Processing		Merox	Hydrotreatment
Delivery to Airport	PL	PL	PL
Airport Handling			
Settling	Yes	Yes	Yes
Clay Filtration	No	Yes	Yes
F/S	Yes	Yes	Yes

TABLE 2-3

LAT TEST UNITS - COALESCER ELEMENTS

LAT Cart No.	Test Fuel	Coalescer Type	Coalescer Installed	Coalescer Throughput, Gallons		
				Start of Test(1)	To March 31, 1977	To April 30, 1977(1)
E-332	A	CF-1	12/01/76	5,444,266	9,234,416	10,048,123
E-338	A	CF-1	11/20/75	7,104,245	10,436,703	11,041,592
E-333	A	CF-1	02/01/76	4,002,781	5,539,383	5,838,624
E-348	B	CF-2	12/08/74	11,326,866	15,257,099	16,131,577
E-326	B	CF-2	02/18/76	1,981,576	4,804,970	5,543,596
E-313	B	CF-1	02/16/76	1,068,392	4,034,383	4,633,136
E-308	C	CF-1	07/20/75	16,847,520	21,245,553	22,872,874
E-323	C	CF-1	11/19/75		23,355,045	24,663,888
E-304	C	CF-1	07/21/75	19,373,091	15,024,225	16,087,828
E-303	A	CF-2				

---

(1) Calculated data.

TABLE 2-4

LAT TEST UNITS - SEPARATOR ELEMENTS

LAT Cart No.	Test Fuel	Test Separator Type	Separator Installed	Separator Throughput, Gallons				
				To Jan. 31, 1977	To March 31(2)	To April 30	To July 1	To August 1 (2)
E-332	A	SP-2	10/27/76	2,162,736	3,790,150	4,603,857	6,249,287(1)	7,072,002
E-338	A	SP-1	10/27/76	2,122,680	3,332,458	3,937,347	4,790,465(1)	5,217,024
E-333	A	SP-1 & 2 (7 SP-1/6 SP-2)	10/27/76	938,120	1,536,602	1,835,843	-	-
E-348	B	SP-2	12/07/76	2,181,276	3,930,233	4,804,711	8,739,865(1)	10,707,442
E-326	B	SP-1 & 2 (6 SP-1/7 SP-2)	12/06/76	1,346,141	2,823,394	3,562,020	-	-
E-313	B	SP-1	-	-	2,965,991	3,864,121	5,660,380(1)	6,558,509
E-308	C	SP-1	12/13/76	1,143,389	4,398,033	6,025,354	8,176,656(1)	9,252,307
E-323	C	SP-1 & 2 (6 SP-1/7 SP-2)	12/28/76	1,364,267	3,981,954	5,290,797	-	-
E-304	C	SP-2	12/27/76	1,064,139	3,173,346	4,236,949	6,458,984(1)	7,570,001
E-303	A	ST	09/04/72			55,946,073		

---

(1) Single elements removed July 1st for shipment to contractor laboratory.

(2) Calculated data.

TABLE 2-5

TEST DATA SUMMARY

(October 28, 1976)

LAT Cart No.	Test Fuel	Test Separator Type	Charge Density, $\mu C/m^3$ 700 gpm		Time to Final Measurement, Seconds	50% Decay Time, Sec.(1)	Fuel Temp., °F	Separator Throughput M Gal
			Peak	Final				
E-332	A	SP-2	+ 6	+ 5	900	48	54	36.6
E-338	A	SP-1	-60	-48	390	68	55	27.9
E-333	A	SP-1 & 2 (7 SP-1/6 SP-2)	-37	-30	600	64	55	35.8

---

(1) Conductivity less than 2.0 pS/m.

TABLE 2-6

TEST DATA SUMMARY - PERIOD B: FEBRUARY 8, 1977

FUEL TEMPERATURE = 29-34°F

LAT Cart No.	Test Fuel	Test Separator Type	Flow Rate, gpm	Charge Density, $\mu C/m^3$ First Peak	Second Peak	Final	Time(s) to First Peak	Second Peak	Time to 50% Decay	
E-332	A	SP-2	500	- 27	+ 7	-5	10	24	--	
			250	- 6.5						
E-338	A	SP-1	500	-116		+5.5	28		--	
			500	- 55	- 8	--		+12		Repeat
			500	- 77	-15	--		+12		Repeat
E-333	A	SP-1 & 2	500	-110	-43	+7	6	+10	--	
			250	- 68	-46		14	18		
E-348	B	SP-2	500	- 5	-13	-3	33	54	--	
			250	- 5	--	--	26	--		
E-313	B	SP-1	500	- 15	- 8	-9	18	42	--	
			500	- 13	- 8		40	70		Repeat
E-326	B	SP-1 & 2	500	- 6	+ 1	-4	38	+15	--	
			500	- 4	0					Repeat
E-304	C	SP-2	500	+ 5	+12	-1.5	12	47	--	
			500	- 1.5	+ 3		8	21		Repeat
E-308	C	SP-1	500	+ 3	-11	-6.5	25	30	--	
			500	- 8	0		29	42		Repeat
			250	- 30	-12		42	150		
E-323	C	SP-1 & 2	500	- 14		-4				
			250	- 4		-4				

TABLE 2-7

TEST DATA SUMMARY - PERIOD C: MAY 3-4, 1977

FUEL TEMPERATURE = 53-57°F

LAT Cart No.	Test Fuel	Test Separator Type	Flow Rate, gpm	Charge Density, μC/m³ First Peak	Charge Density, μC/m³ Second Peak	Charge Density, μC/m³ Final	Time(s) to First Peak	Time(s) to Second Peak	Time to 50% Decay
E-332	A	SP-2	600	- 9.5	+24	+19.5	8	27	25
				- 7	+25	--	6	16	35
			250	+ 11.5		+ 8.5	29		
E-338	A	SP-1	600	-240	-84	-34	13	24	55
				-120	-58	--	9	30	65
			250	- 56	-52	-50	30	80	38
E-333	A	SP-1 & 2	600	-117		-12	13		30
			250	- 56		-24	18		50
E-348	B	SP-2	600	- 2		- 1	16		
			250	- 1.5		- 1.5	22		220
E-313	B	SP-1	600	- 13	- 4	- 6.5	10	21	110
			250	- 14		-11	45		140
E-326	B	SP-1 & 2	600	- 7.5	- 8.5	- 7	14	38	460
			250	- 7.5	- 8	- 8	54	70	325
E-314	B	SP-1 & 2	600	- 5	-15.5	- 4	10	27	
			250	- 5.5	- 4	- 4	16	35	

TABLE 2-7
(Continued)

TEST DATA SUMMARY - PERIOD C: MAY 3-4, 1977

FUEL TEMPERATURE = 53-57°F

LAT Cart No.	Test Fuel	Test Separator Type	Flow Rate, gpm	Charge Density, $\mu C/m^3$ First Peak	Second Peak	Final	Time(s) to First Peak	Second Peak	Time to 50% Decay	
E-304	C	SP-2	600	+ 3.5	0	+ 2	29	65	220	
			250	- 2	+ 5.5	+ 2	9	37	210	
E-308	C	SP-1	600	- 7	- 4	- 2.5	9	55	280	
				- 6	- 4	- 3.5	18	67	300	Repeat
			250	- 6	- 4	- 4	12	67	340	
E-323	C	SP-1 & 2	600	- 4		- 1.5	24		220	
			250	- 4		- 4	30			
E-303	A	ST	600	--	-27	- 4	--	38	38	Perm. Sep.
			250	- 3	-14.5	- 2	20	42	90	Test 5/4
E-338	A	SP-1	600	-110	-76	-30	10	18	45	Test 5/4
			600	- 84	-29.5	-24	14	65	30	Repeat
			250	- 82	-53	-29	22	43	40	

TABLE 2-8

TEST DATA SUMMARY - PERIOD D: AUGUST 3, 1977

FUEL TEMPERATURE = 72-76°F

LAT Cart No.	Test Fuel	Test Separator Type	Flow Rate, gpm	Charge Density, $\mu C/m^3$			Time(s) to		Time to 50% Decay	
				First Peak	Second Peak	Final	First Peak	Second Peak		
E-332	A	SP-2	600	- 27			20		15	Tank 207 not isolated
			250	- 9	+10	+20	27	50	25	Fuel Varies
E-338	A	SP-1	600	-132	-76	-61	25	40	25	Fuel Varies
			250	- 62	-58	-46	18	33	20	Fuel Varies
			600	- 80	?	-34	20		25	Repeat
E-383	A	SP-1 & 2	600	- 77	?	-35	35	?		Tank 207 not isolated
			250	- 32.5	?	- 8.5	27	?		Fuel Varies
E-348	B	SP-2	500	- 7.5	-24	- 2	20	38	140	
			250	- 3.5	- 8.4	- 3.5	28	55	110	
E-313	B	SP-1	600	- 56	-76	-44.5	13	33	35	
			250	- 43	-66	-46	22	50	40	
E-326	B	SP-1 & 2	600	- 56	-72	-38	8	20	58	
			200	- 37	-65	-38	12	35		
E-311	B	SP-1 & 2	500	- 45	-62	-37	9	21	--	
			250	- 33	-43	-35	23	40	40	
E-304	C	SP-2	500	- 35	- 2	- 3	27	37	420	
			220	- 15	+ 3	- 4.5	42	80	300	
E-308	C	SP-1	600	+ 3	- 7	- 7	13	17		Fuel Varies
			250	- 3.5	+ 2	- 4.5	8	10	150	Fuel Varies
E-323	C	SP-1 & 2	600	- 4	-11.5	- 4	17	30	90	
			250	- 13	-35.5	- 8	26	39	110	

TABLE 2-8
(Continued)

TEST DATA SUMMARY - PERIOD D: AUGUST 4, 1977

FUEL TEMPERATURE = 72-76°F

LAT Cart No.	Test Fuel	Test Separator Type	Flow Rate, gpm	Charge Density, $\mu C/m^3$ First Peak	Charge Density, $\mu C/m^3$ Second Peak	Charge Density, $\mu C/m^3$ Final	Time(s) to First Peak	Time(s) to Second Peak	Time to 50% Decay	
E-332	A	SP-2	600	- 20.5	?	- 2	10		12	Tank 207 isolated
			250	- 15.5	?	- 4	25		15	Tank 207 isolated
E-332	A	SP-2	600	-106	--	-33	13		35	No coalescer
			250	- 28.5	--	-26	13		35	No coalescer
E-338	A	SP-1	600	-106	--	-53	11		25	No coalescer
			250	- 63	--	-61	16		20	No coalescer
			600	- 72	--	-59	13			Repeat
E-338	A	SP-1	600	- 10		- 2	65			Coalescer only
			250	- 3		- 3.5				Coalescer only
E-303	A	ST	600	- 4	-27	- 2	4	20		Perm. Sep.
			250	- 2	- 8	- 1.5	6	28		Perm. Sep.

TABLE 2-9

CALCULATED CHARGE OUTPUT OF COALESCER AND SEPARATOR ELEMENTS

(Based on double peaks in CDM records)

	Fuel	Cart No.	Separator Type	Charge Density, $\mu C/m^3$ (1)		Basis of Calculation
				Separator	Coalescer	
TEST PERIOD B:						
	A	E-332	SP-2	- 30	+ 45	Note 2
				-300	--	
		E-338	SP-1	- 80	+ 90	Repeat
				-100	+ 95	Repeat
	B	E-348	SP-2	- 7	- 20	Note 2
		E-313	SP-1	- 18	- 9	
	C	E-304	SP-2	+ 5	+ 13	Note 2
		E-308	SP-1	+ 3	- 20	
TEST PERIOD C:						
	A	E-332	SP-2	- 12	+ 98	Note 3
		E-338	SP-1	-353	+293	
				-156		Repeat
	B	E-348	SP-2	- 2	--	Note 4
		E-313	SP-1	- 15	+ 12	
	C	E-304	SP-2	+ 4	- 4	Note 4
		E-308	SP-1	- 8	- 3	
	A	E-338	SP-1	-147	+ 65	Note 3
				-127	+140	Repeat
		E-303	ST	0	- 84	
TEST PERIOD D:						
	A	E-332	SP-2	- 61	--	Note 5
		E-338	SP-1	-367	+400	
				-180		Repeat
	B	E-348	SP-2	- 9	- 20	Note 3
		E-313	SP-1	- 82	-125	
	C	E-304	SP-2	- 4	+ 2	Note 4
		E-308	SF-1	+ 4	- 13	

Note: (1) Charge output at maximum flow rate, 600 gpm.
(2) Assuming hyperbolic charge decay with ion mobility = $0.3 \times 10^{-8} m^2/v\text{-}s$.
(3) Assuming ohmic charge decay at conductivity of 0.54 pS/m.
(4) Assuming hyperbolic charge decay with ion mobility = $1.0 \times 10^{-8} m^2/v\text{-}s$.
(5) Assuming ohmic charge decay at conductivity of 0.69 pS/m.

TABLE 2-10

CALCULATED CHARGE CONTRIBUTION OF SEPARATE COALESCERS AND SEPARATORS

(Based on Special Tests with Fuel A of 0.69 pS/m Conductivity from Isolated Tank)

LAT Cart No.	Separator Type	Filters Tested	Flow Rate	Charge Density, $\mu C/m^3$ Separator	Charge Density, $\mu C/m^3$ Coalescer	Basis of Calculation
Peak CDM Values						
E-332	SP-2	Both	600		+254	Combined
		Elements	250		+ 78	Data on two runs
		SEP only	600	-177	--	Minus SEP only tests
		SEP only	250	- 63	--	Direct
E-338	SP-1	SEP only	600	-182 (-120)		Direct
		SEP only	250	-119		
		COAL only	600	--	-107	Direct
		COAL only	250	--	- 40	
E-303	ST	Perm SEP	600	- 5	- 58	
		and COAL	250	- 3	- 16	
Final CDM Values						
E-332	SP-2	Both	600		+ 65	Combined
		Elements	250		+325	Data on two runs
		SEP only	600	- 49		Minus SEP only tests
		SEP only	250	- 98		Direct
E-338	SP-1	SEP only	600	- 88 (-79)	--	Direct
		SEP only	250	-150	--	
		COAL only	600	--	- 5	Direct
		COAL only	250	--	- 36	Direct
E-303	ST	Perm SEP	600	- 3	--	
		and COAL	250	- 2	--	

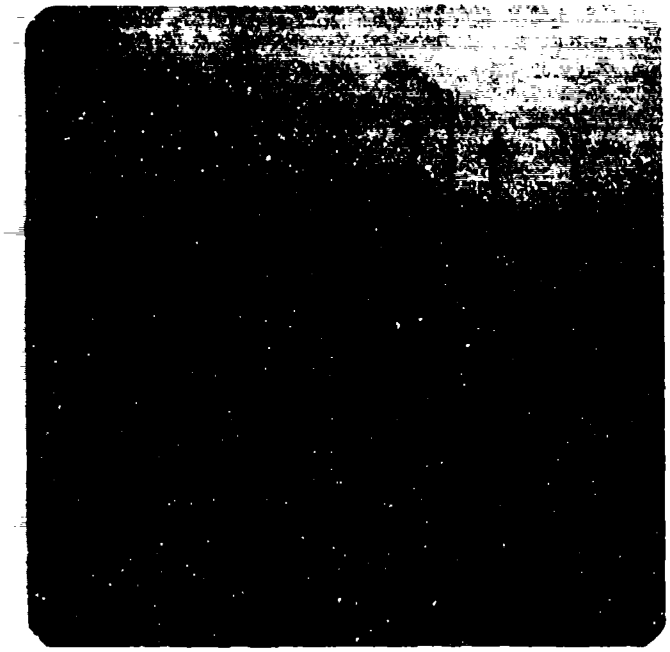
TABLE 2-11

RELATIVE CHARGING TENDENCIES OF SEPARATORS

	Ratio of Charge Densities of Separator SP-1 / Separator SP-2 at 600 gpm			
Fuel:	A	B	C	Source of CD Ratio
Test Period				
B	2.7-10	2.6	0.6	Peak Charge
C	10.5-30	7.5	2.0	Peak Charge
D	3 - 6	9.2	1.0	Peak Charge
D	1 1.9 (250 gpm)			SEP Tests Peak Charge
D	1.6- 1.8			SEP Tests Equil. Charge

FIGURE 2-1

TYPICAL LAT HYDRANT CART
(With Hydraulic Lift)



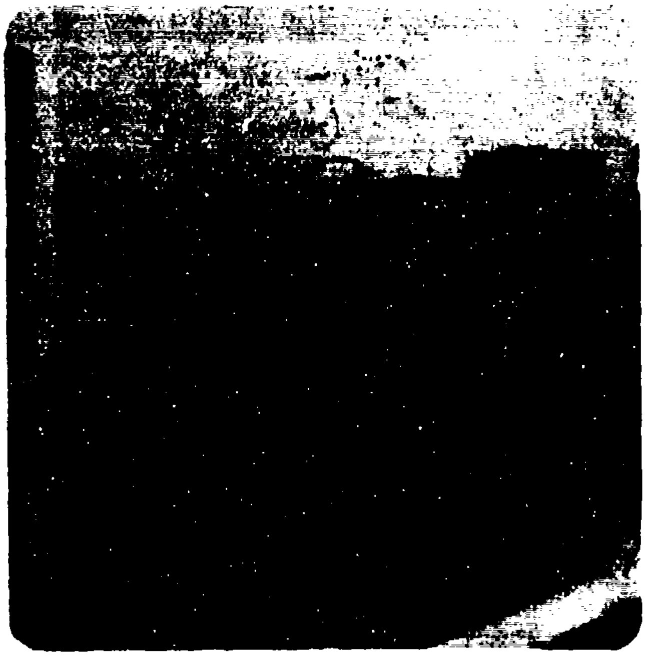


FIGURE 2-2

HYDRANT CART PIPING

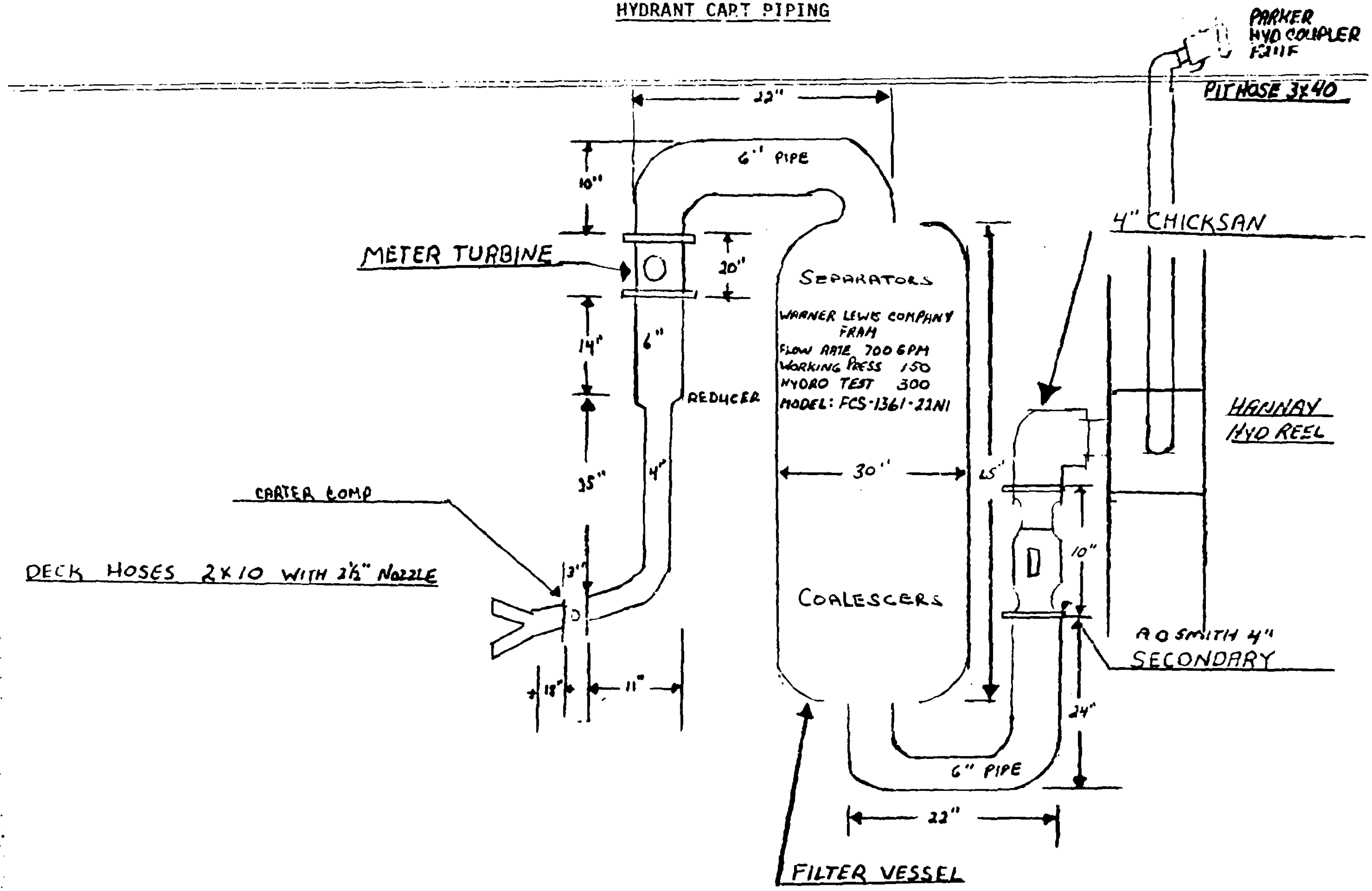


FIGURE 2-3

INSTRUMENT MANIFOLD WITH CHARGE DENSITY METER

FIGURE 2-4

TEST MANIFOLD

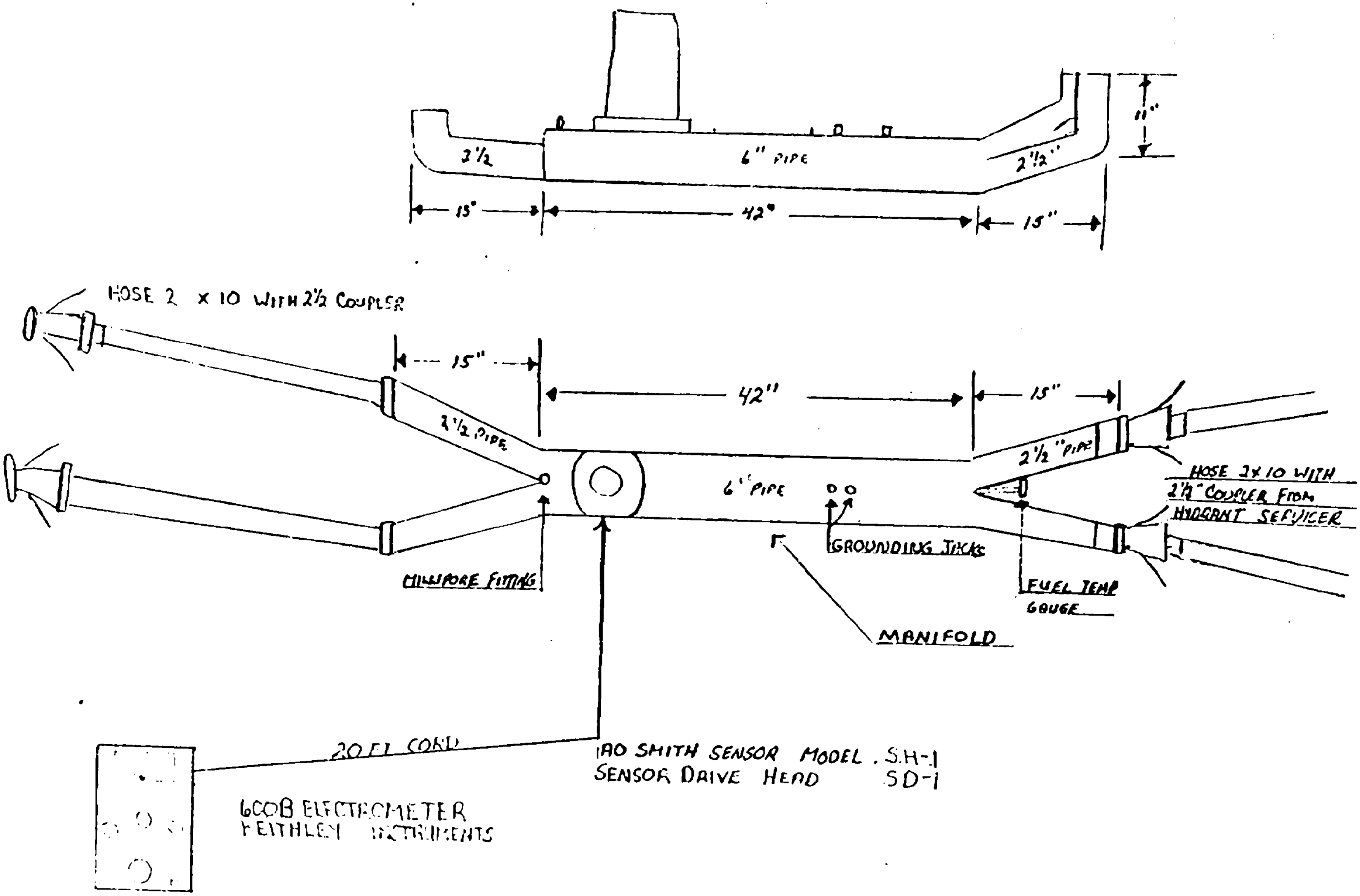
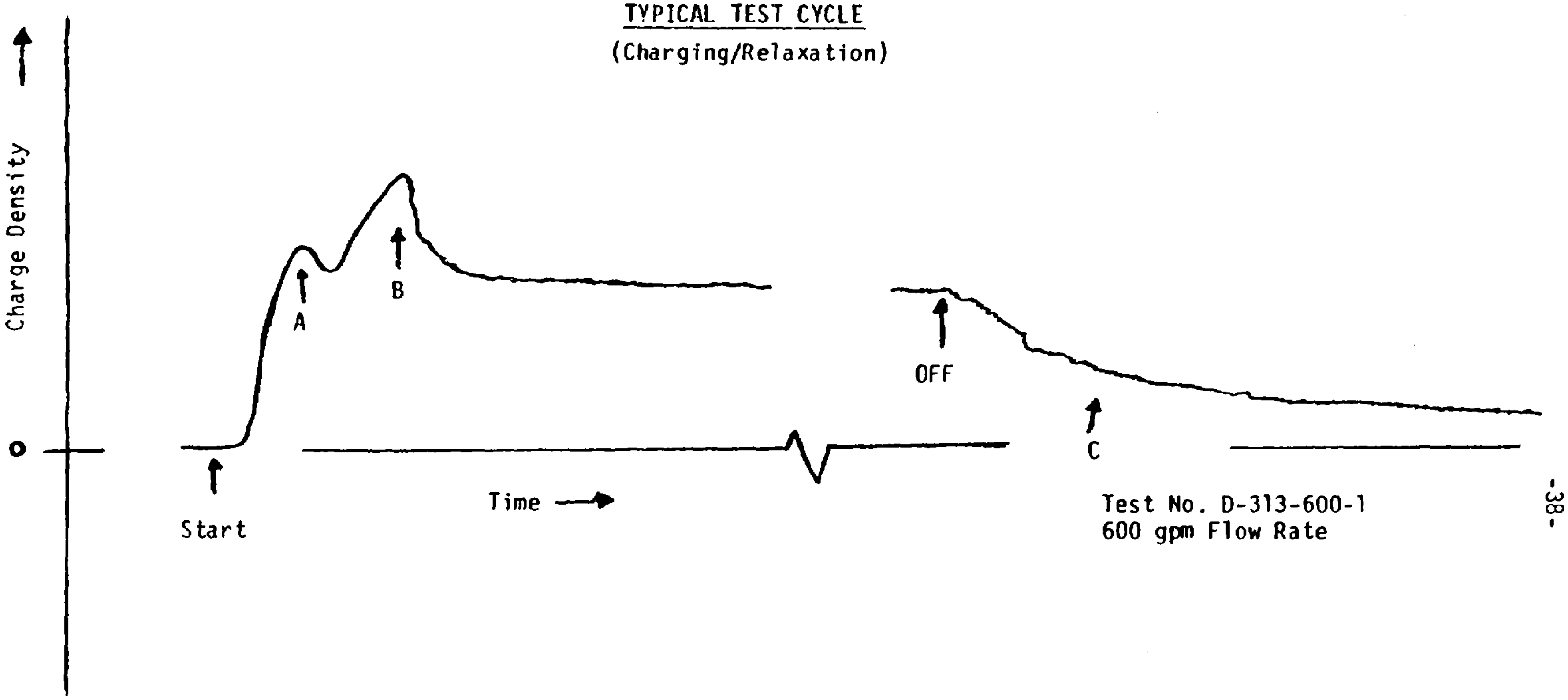


FIGURE 2-5

TYPICAL TEST CYCLE
(Charging/Relaxation)



Test No. D-313-600-1
600 gpm Flow Rate

A = Separator Peak

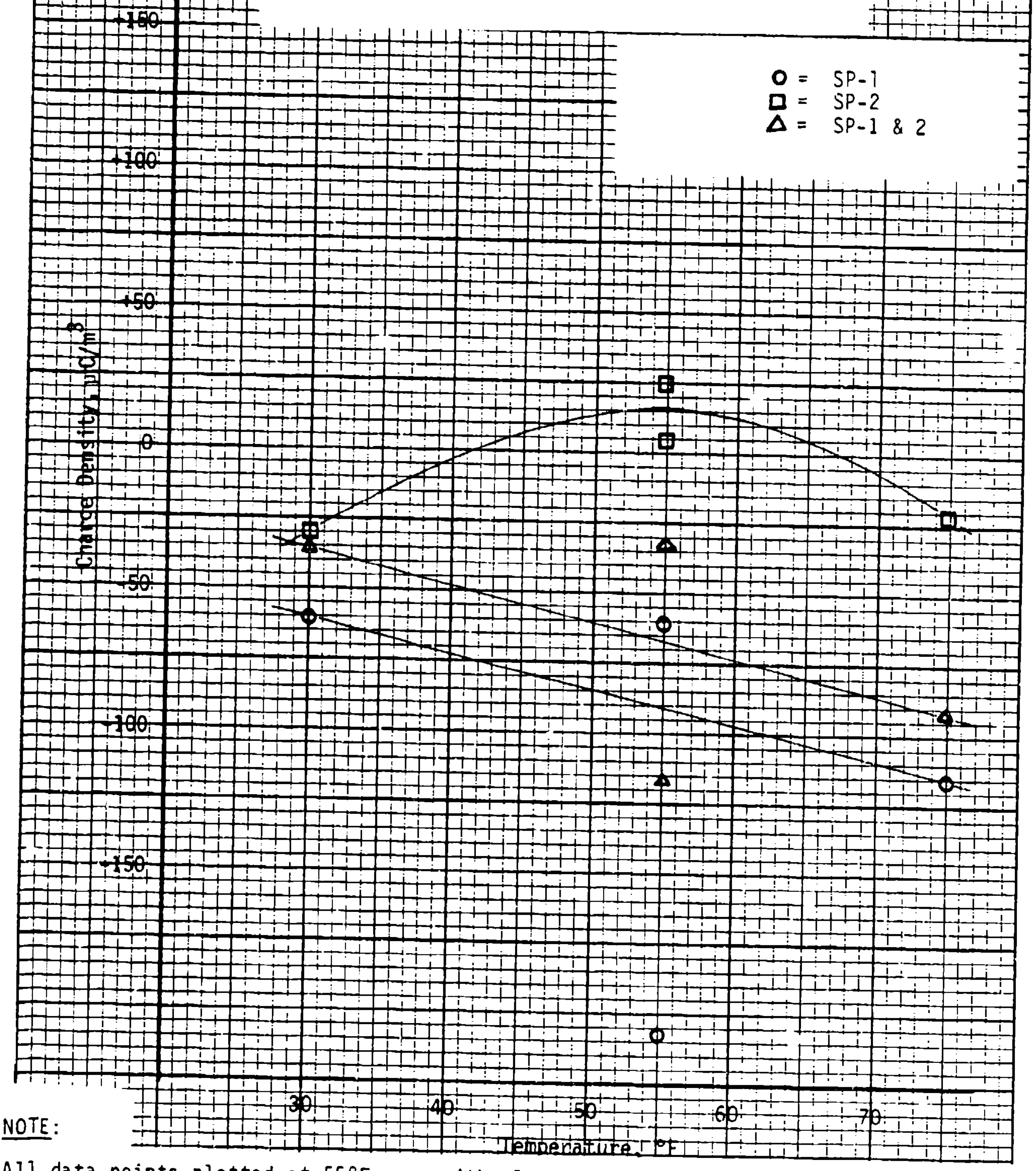
B = Combined Coalescer/Separator Peak

C = Relaxation After Flow Stopped

FIGURE 2-6

CHARGING VERSUS TEMPERATURE - FULL FLOW

FUEL A



NOTE:

All data points plotted at 55°F were with almost brand-new separator elements that may not have reached equilibrium.

For specific information regarding the date of testing, refer to Tables 2-5 through 2-8.

FIGURE 2-7

CHARGING VERSUS TEMPERATURE - FULL FLOW

FUEL B

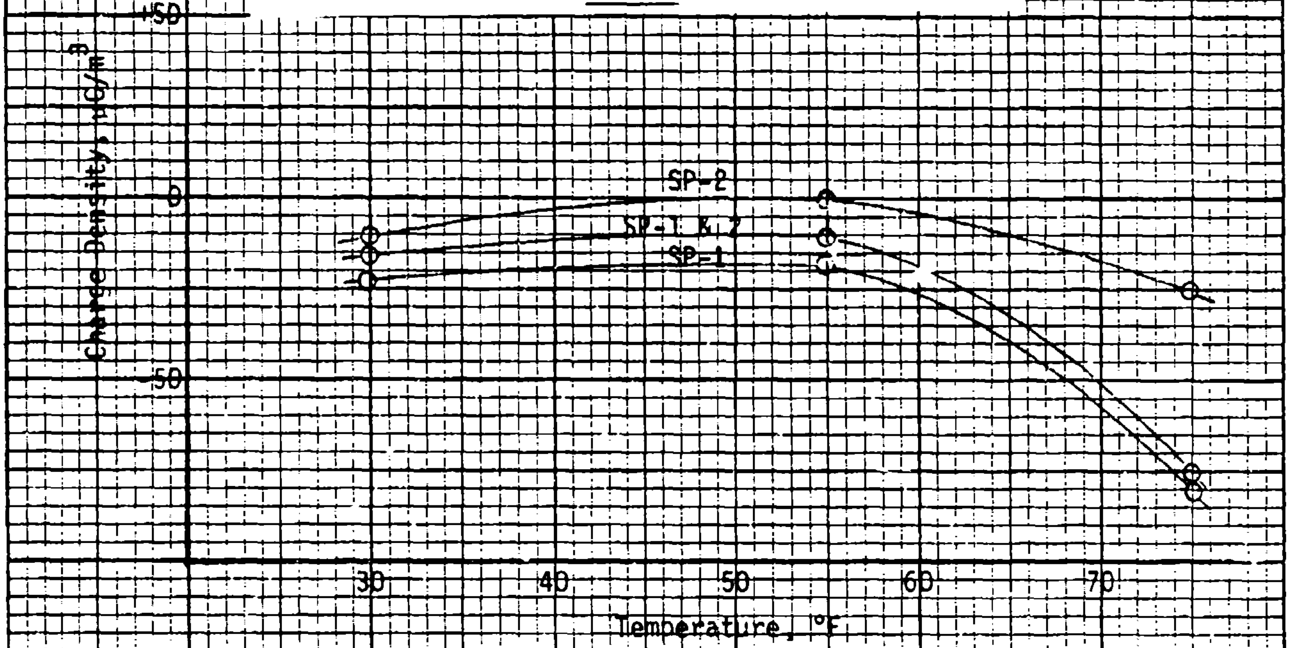
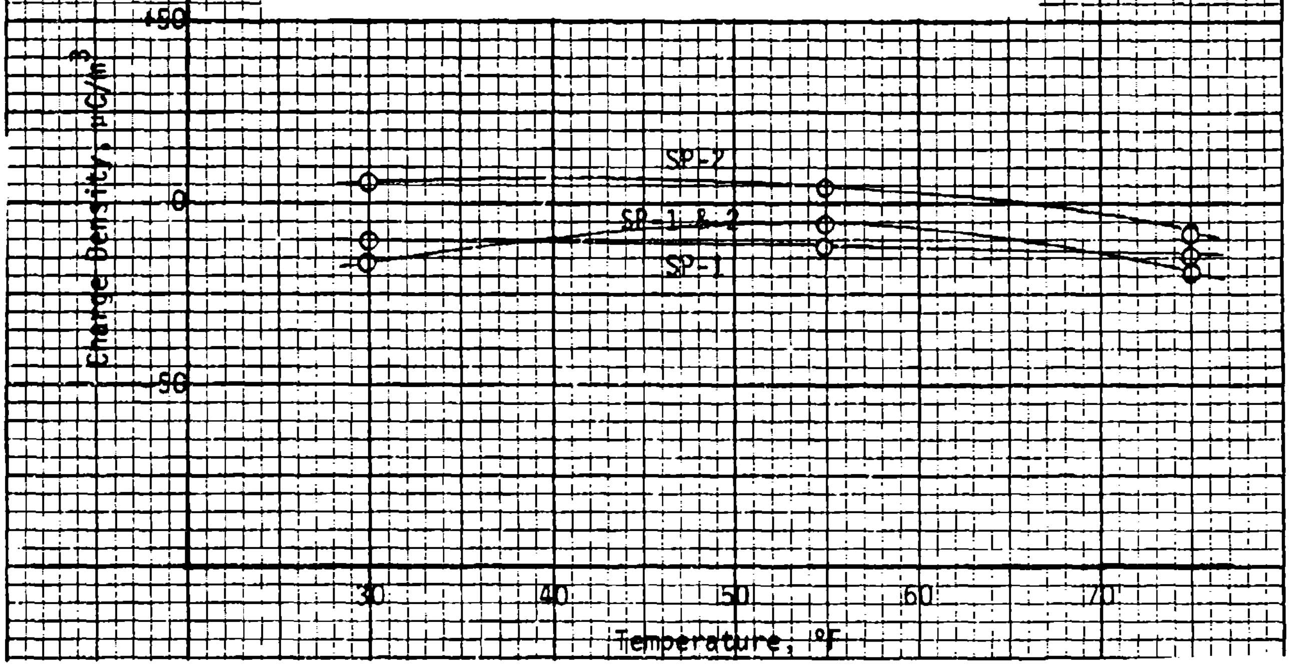


FIGURE 2-8

CHARGING VERSUS TEMPERATURE - FULL FLOW

FUEL C



NOTE:

For specific information regarding the date of testing, refer to Tables 2-5 through 2-8.

CHAPTER 3

LABORATORY AND RIG TEST REPORT

LABORATORY AND RIG TEST REPORT

A. Objective and Scope

The objective of the laboratory phase of the Field Test Program discussed in Chapter 2 was to apply laboratory tests and Filter Charging Rig procedures to the particular fuels and elements tested in the field to verify the validity of small-scale testing for electrostatic charging tendency.

Small-scale tests take place for individual elements in the Filter Charging Rig developed under CRC contract(5) and the Ministatic Test Procedure (MST) described in Reference 4.

B. Charging Test Rig

1. Test Facility

A schematic flow diagram of the CRC Filter Charging Test Facility appears in Figure 3-1. A detailed description of this test rig and the procedures developed to test the charging tendency of separator elements appears in Reference 5. The procedure for the Aviation Fuel Filter Electrical Charging Test is given in Appendix C. The heart of the rig are two electrically isolated test sections in parallel with separate flow control which can accommodate separator elements, one of which is normally used as a reference. For testing coalescers, the test sections were modified to reverse flow patterns. The coalescer elements could also be installed in the precharge vessels, also electrically isolated, in a position relative to a separator as that normally used in field filter separators.

During tests in a flowing system, five electrical measurements are made simultaneously: the output of three charge density meters positioned ahead of the test vessels (CD-1) and downstream of each test vessel (CD-2 and CD-3), plus streaming currents that flow from each electrically isolated test section or precharge section to ground through Keithly electrometers. Close control is maintained over fuel quality by using the clay filter to reduce conductivity if necessary, and by using the cooler and tank atmospheric control to adjust fuel temperatures and dissolved water content.

2. Test Procedure

The test procedure involves three different fuel conditions identified as follows:

	Fuel Temperature, °F	Total H_2O Control uppm
Sequence 1	20	25 ± 5
Sequence 2	10	25 ± 5
Sequence 3	10	45 ± 5

Each filter is tested at its rated flow which is 40 gpm for Group I coalescers and 100 gpm for separators. The following individual and combinations of filters were tested:

Used Group I Coalescer - Cart E-332
Used Group I Coalescer - Cart E-338

Used Separator SP-2 - Cart E-332
Used Separator SP-1 - Cart E-338

New Separator SP-2
New Separator SP-1 (reference element)

Used Coalescer I (Cart E-332) + Separator SP-2 (Cart E-332)
Used Coalescer I (Cart E-338) + Separator SP-1 (Cart E-338)

Application of the resulting electrical measurements to the various combinations of filters for data analysis is illustrated graphically in Figure 3-2.

Jet A Rig Fuel D displayed a conductivity of 1.8 pS/m at 21°C. Although similar in conductivity to the fuel used in test development (see Reference 5), its charging tendency with Separators SP-1 and SP-2 was higher as illustrated in Table 3-1.

C. Tests of Field and Rig Test Fuels

The three commercial Jet A fuels from the field test program at O'Hare Field were tested for charging tendency using the Ministatic Test Procedure (MST) described in Reference 4. Several different separator filter media were employed including Separator SP-1 and SP-2 types used for field tests. MST test results at 23°C are shown in Table 3-2 comparing three O'Hare test fuels with Rig Fuel D.

MST data indicate that Separator SP-1 is more active than Separator SP-2 with all fuels. With other filter media, Fuels B and C are similar to Fuel D in ranking. Fuel C appears to have the lowest charging tendency, Fuel B the highest. The Fuel A sample was taken in 1976, about nine months before the last test sequence of August 1977; it is intermediate in charging tendency and similar to Rig Fuel D.

Field data taken at 23°C indicated in Chapter 2 that Fuel C is the least active, Fuel A the most active, and that Separator SP-1 is consistently higher charging than Separator SP-2. (The Fuel A sample was taken following Test Period A, and examination of Figure 2-6 suggests an increase in Fuel A's charging tendency between Period A and Periods B, C and D.) These field data would substantiate the usefulness of the MST test as a small-scale laboratory charging tendency test, since it ranks both fuels and separator media in the correct order.

D. Tests of Field Test Filter Elements

1. New Separators

Shortly after the sequence field tests of October 28, 1976 (see Table 2-5), new separators of the SP-1 and SP-2 type were sent to Exxon for evaluation in their single element Filter Charging Rig. In this rig test, Jet A Fuel D is recirculated through parallel test sections containing the separator elements. Flow is separately controlled to 100 gpm through each section. Static charge is measured by streaming current from the electrically isolated test sections. The readings stabilized after a "break-in" period of several hours and a reading taken at four hours (24,000 gallons through each element) is shown in Table 3-3, compared with the O'Hare Test Data shown in Table 2-5.

The Exxon rig indicates that Separator SP-1 is more active than Separator SP-2 by a factor of 2-3. The October 28, 1976, tests with Fuel A also show the new Separator SP-1 to be more active, but the lower throughput per element, less than one hour of "break-in," suggests that equilibrium static charging values may not have been reached in October 1976 field tests.

2. Used Coalescers and Separators from Field Testing

Detailed test results on the 146 runs conducted and analyzed are on file at the CRC office.

Streaming current measurements of individual filter elements at rated flow for Sequences 1 and 2 are plotted in Figure 3-3 against fuel temperature. From these data, it is evident that Used Group I coalescers charge at a much higher level than either separator, and that each filter type shows increased charge output with increased temperature. Separator SP-1 charges at a higher level than Separator SP-2, and there appear to be no large differences between used and new separators.

In Figure 3-4, Sequences 2 and 3 are compared to show the effect of dissolved water content on filter charging. As before, it is evident that used Group I coalescers charge at a much higher level than either separator, and that each filter type shows increased charge output with increasing water content. Separator SP-1 again displays a higher charge level than Separator SP-2, and new elements are similar to used elements.

In Figures 3-5, 3-6, and 3-7, the charge density measured in the charge density meter (CDM) in CD-2 and CD-3 is plotted against charge density calculated from streaming current from the filter case for Sequence 1, 2, and 3, respectively.

The excellent correlation between calculated and measured values of charge density is shown in Table 3-4. Regression analysis for all sequence test data on elements tested in the test section produced a correlation coefficient of 0.969 and a slope approaching unity.

Data analysis relating CDM readings to filter current readings requires knowledge of the volumes of fuel within the test rig at various flow rates. These data appear in Table 3-5, together with estimated residence time in seconds for various flow rates. Charge imparted to the fuel by flow through a filter element will relax to an extent that depends upon the available residence time and also the effective conductivity of the fuel.

Coalescer elements were also tested in the precharge vessel and, as noted in Table 3-4, a correlation coefficient of 0.994 was obtained when regression analysis was performed on measured versus calculated charge densities. These tests, however, produced a slope only half as large as the test data obtained with elements in the test section vessels. The explanation for this difference can be found by examining the residence time in Table 3-5; with the precharge vessel about 17 seconds of residence time exists between the element and CD-1, but with the test section, the time between the element and CD-2 is only 1.8 seconds.

The tests involving the combination of elements (i.e., coalescers in the precharge vessel and separators in the test section) were analyzed by subtracting the CD-1 inlet charge from the measured charge from the test section filters. As noted in Table 3-4, a correlation coefficient of 0.962 was obtained when all the data were regressed and a slope of the measured versus calculated line approached unity. Figure 3-8 is a plot of the resulting regression. This analysis confirmed a finding of the original test rig development program that the charge developed by a filter element (in this case, new or used Separators SP-1 or SP-2 or a reference separator) is independent of the inlet charge, and that the resultant output charge in flowing fuel represents the algebraic sum of the contributions of both elements.

E. Analysis of Field Data

1. Correlation of Rig and Field Results

The comparison between rig and field data on the used filters from Carts E-332 and E-338 should be made at the fuel temperature of the August 3-4 test period: about 22°C and at rated flow conditions. Table 3-6 lists the field data on prior charge levels extracted from Chapter 2: Table 2-10 at 600 gpm and 250 gpm test conditions under the columns on calculated separator and coalescer charge. Under comparable conditions of flow, the rig shows a lower charge level for Separator SP-2 and an equivalent or higher charge level for Separator SP-1. Higher charge levels are measured at 40 percent rated flow in both field and rig. Polarity is the same for the Fuels A and D. In other words, the rig results on filter charge support the field data showing Separator SP-1 to be more active, but the advantage of Separator SP-2 as a low-charging filter appears somewhat greater in rig data than in field data. The rig data also indicate used separators to charge at 37-60 percent higher levels than new separators.

Under Sequence 1 rig conditions, both used Group I coalescers from Carts E-332 and E-338 showed equally high charge levels of negative polarity. This result corresponds directionally to field data which indicated somewhat lower negative peak charge for the E-338 coalescer when measured separately. (Calculations for the E-332 coalescer suggested equivalent but positive charge for rig and field data.)

The peak values observed in field testing of coalescers separately are the only measurements that can be compared with rig tests, because equilibrium values in the field were close to zero (from -3.5 to +2 $\mu C/m^3$). Even so, the peak was observed 65 seconds after flow started, although there is nominally only 24 seconds of residence time between coalescers and CDM at 600 gpm. The calculated values in the feed are highly dependent upon effective conductivity of the fuel. If Fuel A were comparable to Rig Fuel D in conductivity, the coalescer would appear to be charging close to the levels observed in the Filter Charging Rig.

2. Laboratory MST Data on Field Filters and Fuels

After completion of the rig tests on used filters from O'Hare, laboratory tests using the Ministatic Charging Tendency (MST) test were carried out using both Fuel D and a sample Fuel A taken soon after the August 3-4, 1977, field tests and stored until early 1979. Data under comparable temperature and fuel water content conditions (indicated by relative humidity of test environment) are shown in Table 3-7.

With Rig Fuel D, Separator SP-1 showed higher charge levels than Separator SP-2 with both new and used elements. The MST data on sections of used separators generally support the rig data on the full-scale elements. On the other hand, Fuel A appears to be much more electrically active than Fuel D and producing charge of opposite polarity. This conclusion is at variance with the evidence of field versus rig data on separator elements. It is likely, therefore, that Fuel A changed in storage over eighteen months. One piece of supporting evidence for this speculation can be seen in the data for a 1975 sample of Fuel D held in storage almost four years which also showed considerable pro-static tendency and a reversed polarity with the same filter media. Data on SP-10 paper, the original reference media used in MST testing, also confirms the greater activity of stored fuels.

The test procedure developed in Reference 5 involves both rig testing and backup MST testing at various temperatures and water contents with and without pro-static additive. This portion of the test procedure was carried out on the used O'Hare separator media using clay-treated Fuel D. Data appear in Table 3-8.

With base fuel, increases in either temperature or water content of fuel had negligible or small positive MST charge effects on the negative charge produced by either new or used Separators SP-1 and SP-2. When a pro-static additive (G-178) was introduced, however, MST values reversed to positive polarity and showed increases with both temperature and water content. Separator SP-1, both new and used, was much more responsive to temperature and water content increases than Separator SP-2. Used Separator SP-1 was more active than new material, while the reverse was true for Separator SP-2.

3. Water Saturation of Test Fuels

The test procedure of Reference 5 also includes a requirement for determining the water saturation curve for each test fuel in order to translate humidity measurements into actual water contents. Figure 3-9 represents the water saturation curves for both Fuel A and Rig Fuel D. They are very similar. Shown in Figure 3-9 are actual versus calculated water contents for a fuel exposed to 24 percent relative humidity. Agreement is excellent, indicating the usefulness of a saturation curve for predicting actual water levels.

F. Summary of Comparisons - Rig Versus Field Results

Rig Fuel D used in the CRC Filter Charging Rig was shown to be roughly similar to Field Test Fuel A in charging characteristics as measured by laboratory scale MST tests (Table 3-2). The fuels were also similar in conductivity (Table 3-2) and in water saturation (Figure 3-9). In Table 3-9, the charging comparisons between test rig and field for both new and used separators and for coalescers are summarized. The correlation between rig and field data can be rated good to excellent for separators and good for coalescers when run on a comparable fuel.

G. Conclusions

- The field test program established that separators manufactured by Manufacturer F produced about twice as much electrostatic charge with most fuels as separators manufactured by Manufacturer V. These differences were verified in the Filter Charging Rig developed under CRC contract.

- Both direct and indirect field measurements established that coalescer elements produced as much or more electrostatic charge as separators. With low-conductivity fuels, coalescer charging affected the output of two-stage filter/separators, either adding to or neutralizing the separator charge. The high level of coalescer charging was verified by tests on used elements in the Filter Charging Rig.

- Charging levels increased with the effective conductivity of fuels and were highest with fuels that had not been clay-treated. The clay-filtration process not only removes species that affect conductivity, but also reactive species that contribute to electrostatic charge.

- Charging levels increase with temperature, a characteristic verified by the Filter Charging Rig. Charge levels also increase with fuel water content, but this rig result could not be verified in the field.

- Laboratory tests confirmed field results that Field Fuel A was the most active, Fuel C the least active fuel, and Fuel B the intermediate active fuel in terms of charging tendency.

- Field tests supported rig data showing that separator charging is independent of inlet charge, but the inlet charge produced by the coalescer is highly dependent upon system geometry (residence time) and fuel conductivity.

- Used filter elements in general charged at higher levels than new elements, but the increased activity in the field was due to higher temperatures more than to greater throughput.

- When all comparisons were made, laboratory testing of fuels and filter media by either small-scale bench test or filter rig results was shown to be verified very well by tests in the field.

- Finally, none of the field data suggested that charge levels produced in simulated fueling of aircraft with low-conductivity (non-additive) fuels reached a hazardous level.

H. Recommendations

- The CRC Filter Charging Rig provides a design and procedure that is appropriate to apply in predicting the charging characteristics of filter elements either new or used and is recommended for use by industry in predicting field performance.

- Coalescer elements which can charge at equal or higher levels than separators should be evaluated as thoroughly as separators. A smaller-scale test for coalescer media similar to the MST test for separators should be developed.

TABLE 3-1

COMPARISON OF JET A RIG FUELS

	Fuel Conductivity, pS/m (By ASTM D 3114)	Measured Charge Density, $\mu C/m^3$	
		New Separator SP-2	New Separator SP-1
1976/77 Test Fuel*	2.4 @ 20°C	-14	- 45
1978 Test Fuel	1.8 @ 21°C	-53	-100

---

* Run 29 test data from Reference 5.

TABLE 3-2

CHARGING TENDENCY OF JET A TEST FUELS

(Ministatic Tests at 23°C)

Fuel	A	B	C	D	
Conductivity, pS/m (by ASTM D 3114)	2	0.93	0.98	1.5	
Filter Media	MST Charge Density, μC/m³ (Average of 2-3 Tests)				
Test Condition	Dry (20% R.H.*)				Wet (90% R.H.*)
Separator SP-2	9	35	8	19	24
Separator SP-1	62	140	19	103	63
Prefilter PF	--	90	27	70	83
Monitor G-1	17	75	8	49	58

---

* R.H. = Relative Humidity.

TABLE 3-3

CHARGING TENDENCY OF NEW O'HARE TEST SEPARATORS

Test	Exxon Rig	O'Hare Sequence 1 October 28, 1976(1)
Jet A Fuel	D	A
Conductivity, pS/m (by ASTM D 3114)	1.5	< 2
Throughput (Gal)/Element	> 24000	~2200
Test Temperature, °F	65	55

Filter Media	Charge Density, μC/m³	
Separator SP-1	-53	-48 (Cart E-338)
Separator SP-2	-21	+ 5 (Cart E-332)
Separators SP-1 & 2	--	-30 (Cart E-333)

---

(1) Data from Table V.

TABLE 3-4

REGRESSION ANALYSIS OF MEASURED CHARGE DENSITY VERSUS CALCULATED CHARGE DENSITY

(Sequence Runs)

			Regression Analyses (Combined Sequence 1, 2, 3)			
	PF(2)	SY(2)	Correlation Coefficient r^2	Standard Deviation σ	Intercept b	Slope m
SC vs. CD(1) (x) (y)	1	1	0.994	3.95	-53.7	0.513
	2	1				
SC vs. CD (x) (y)	0	2	0.969	16.26	- 1.97	0.960
	0	3				
	0	4				
	0	5				
	0	6				
	0	7				
SC vs. CD - CD_1(Ave) (x) (y)	0	2	0.962	18.24	11.61	0.987
	0	3				
	0	4				
	0	5				
	0	6				
	0	7				
	1	3				
	1	4				
	2	3				
	2	5				
	3	3				
	3	4				
	4	3				
	4	5				

---

(1) SC = Streaming Charge, $\mu C/m^3$, calculated from filter current.
CD = Charge Density, $\mu C/m^3$, measured from charge density meter.

(2) See Figure 3-2.

TABLE 3-5

CRC FILTER CHARGING TEST FACILITY FLOW VOLUMES AND RESIDENCE TIMES

	Flow Volumes			Residence Time, Sec.				
	in	Gal.	gpm:	40	80	100	140	200
P.C. (Insul.) to CD-1 Relax Closed	1131	4.9		7.4	3.7	-	2.1	1.5
CCN-11 to P.C. Insul.	1500	6.5		9.8	4.9	-	2.8	2.0
P.C. (Insul.) to CD-1 Relax Open	9663	41.8		62.7	31.4	-	17.9	12.5
CD-1 to Split	164	0.7		1.1	0.5	-	0.3	0.2
Split to Ref. (Insul. In)	234	1.0		1.5	-	0.7	-	-
CD-1 to Ref. (Insul. In)	392	1.7		2.6	-	1.0	-	-
Ref. (Insul.) to Elem. (Ext.)	502	2.0		3.0	-	1.2	-	-
Elem. In (Int.) to Ref. (Insul. Out)	201	0.9		1.4	-	0.5	-	-
Ref. (Insul. Out) to CD-3	193.7	0.8		1.2	-	0.5	-	-
Split To Test (Insul.)								
Coalescer	140	0.6		0.9	-	0.4	-	-
Separator	234	1.0		1.5	-	0.6	-	-
CD-1 to Test (Insul.)								
Coalescer	304	1.3		2.0	-	0.8	-	-
Separator	392	1.7		2.6	-	1.0	-	-
Inside Coalescer	176	0.8		1.2	-	0.5	-	-
Outside Coalescer	746	3.2		4.8	-	1.9	-	-
Test (Insul. Out) to CD-2								
Coalescer	288	1.2		1.8	-	0.7	-	-
Separator	193.7	0.8		1.2	-	0.5	-	-

TABLE 3-6

COMPARISON OF FIELD VERSUS RIG DATA

CHARGING TENDENCY OF USED O'HARE FILTER ELEMENTS

	Cart E-332		Cart E-338	
	Field	Rig	Field	Rig
Fuel	A	D	A	D
Fuel Temperature, °C	22	22	22	22
Water Content, ppm	?	25	?	25
Rated Flow, gpm	600 --	100 (Sep) 40 (Coal)	600 --	100 (Sep) 40 (Coal)
	---------SP-2----------		---------SP-1---------	
Separator				
Charge Density, μC/m^3				
@ 100% FR	- 49	- 29(1)	- 88	-113(2)
@ 40% FR	- 98	- 36(1)	-150	-123(2)
Coalescer				
Charge Density, μC/m^3				
@ 100% FR	+254 (Peak)	-270(3)	-107 (Peak)	-275(3)
@ 40% FR	+ 78 (Peak)	--	- 40 (Peak)	--
@ 100% FR	+ 65 (Eq.)		- 5 (Eq.)	
@ 40% FR	+325 (Eq.)		- 36 (Eq.)	

---

(1) A new Separator SP-2 element showed -16 μC/m^3 (100% rated flow) -23 μC/m^3 (40% rated flow).

(2) A new Separator SP-1 element showed -81 μC/m^3 (100% rated flow) -92 μC/m^3 (40% rated flow).

(3) Average of four separate tests.

TABLE 3-7

COMPARISON OF FIELD VERSUS RIG FUELS - LABORATORY

(MST Charging Tendency with Filter Media)

	Fuel A	Rig Fuel D(1)	Rig Fuel D (1975 Sample)(2)
Temperature, °C	22	22	22
Relative Humidity	24	24	24
Fuel Conductivity, pS/m	0.69	4.07	6.9
Separator Media	Charge Density $\mu C/m^3$		
New SP-1	129	-72	1180
New SP-2	27	-50	480
Used SP-1 (Cart E-338)	960	-75	720
Used SP-2 (Cart E-332)	-406	-50	480
New SP-10(3)	630	330	1710
Used SP-10	5180	--	--

---

(1) Rig fuel sampled November 1978 after used filter media tests.

(2) Retained sample of 1975 fuel from same source.

(3) Original reference media for MST testing.

TABLE 3-8

MST DATA ON O'HARE SEPARATORS - RIG FUEL

(Temperature-Humidity Effects)

	Ministatic Charge, $\mu C/m^3$			
Fuel	Tank 26 Bwy. TFA(1) - 1978 Stock			
Temperature, °F	75	74	97	95
% Relative Humidity	24	95	25	95
KF, ppm H_2O	32	80.5	24.5	96
Fuel Conductivity, pS/m	1.72	2.29	2.58	2.0
Filter Media				
SP-10	15	115	120	270
SP-10 1/2*	235	1740	460	2100
SP-1	-35	-10	-15	-12
SP-2	-40	-22	-25	-18
SP-1 (Cart E-338)	-55	-22	-30	-25
SP-2 (Cart E-332)	-25	-20	-10	-15

---

(1) Sample of rig fuel taken January 10, 1979, showed 10 pS/m fuel conductivity and was clay-filtered.

* Used elements.

TABLE 3-8
(Continued)

MST DATA ON O'HARE SEPARATORS - RIG FUEL + ADDITIVE

(Temperature-Humidity Effects)

	Ministatic Charge, $\mu C/m^3$							
Fuel	Tank 26 + 20 ppm G-178				Tank 26 + 100 ppm G-178			
Temperature, °F	75	74	97	95	75	74	97	95
% Relative Humidity	24	95	25	95	24	95	25	95
KF, ppm H_2O	29.5	84	27.5	81.5	28	88	25	89.5
Fuel Conductivity, pS/m	10.3	17.8	12.3	22.4	12.3	18.4	15.5	21.2
Filter Media								
SP-10	1050	24000	1550	16500	1740	24300	1650	23000
SP-10 1/2*	1860	27000	3100	26500	3300	25200	4800	23500
SP-1	275	8700	205	1300	410	16000	330	3900
SP-2	210	720	210	900	460	2400	420	1300
SP-1 (Cart E-338)	235	5000	430	5300	710	14000	680	6400
SP-2 (Cart E-332)	145	300	100	360	325	800	300	570

---

* Used elements.

TABLE 3-9

SUMMARY OF CHARGING TENDENCY COMPARISONS - RIG VERSUS FIELD DATA

	Rig Results	Field Results	Degree of Correlation	Source
Fuel	D	A	Good	
Fuel Conductivity, pS/m	1.8	0.69		
Fuel Water Saturation	Equivalent			Figure 3-9
Separator Charge Density, $\mu C/m^3$				
New				Table 3-2
SP-1	- 53	- 48	Excellent	
SP-2	- 21	+ 5	Fair	
Used				Table 3-6
SP-1	-113	- 88	Good	
SP-2	- 29	- 49	Good	
Coalescer Charge Density, $\mu C/m^3$				
Used				Table 3-6
Cart E-338	-275	-107*	Fair	
Cart E-332	-270	+254*	Good(1)	

---

(1) Reverse polarity of calculated field result.

* Peak values.

FIGURE 3-1

FLOW SCHEMATIC

CRC FILTER CHARGING TEST FACILITY

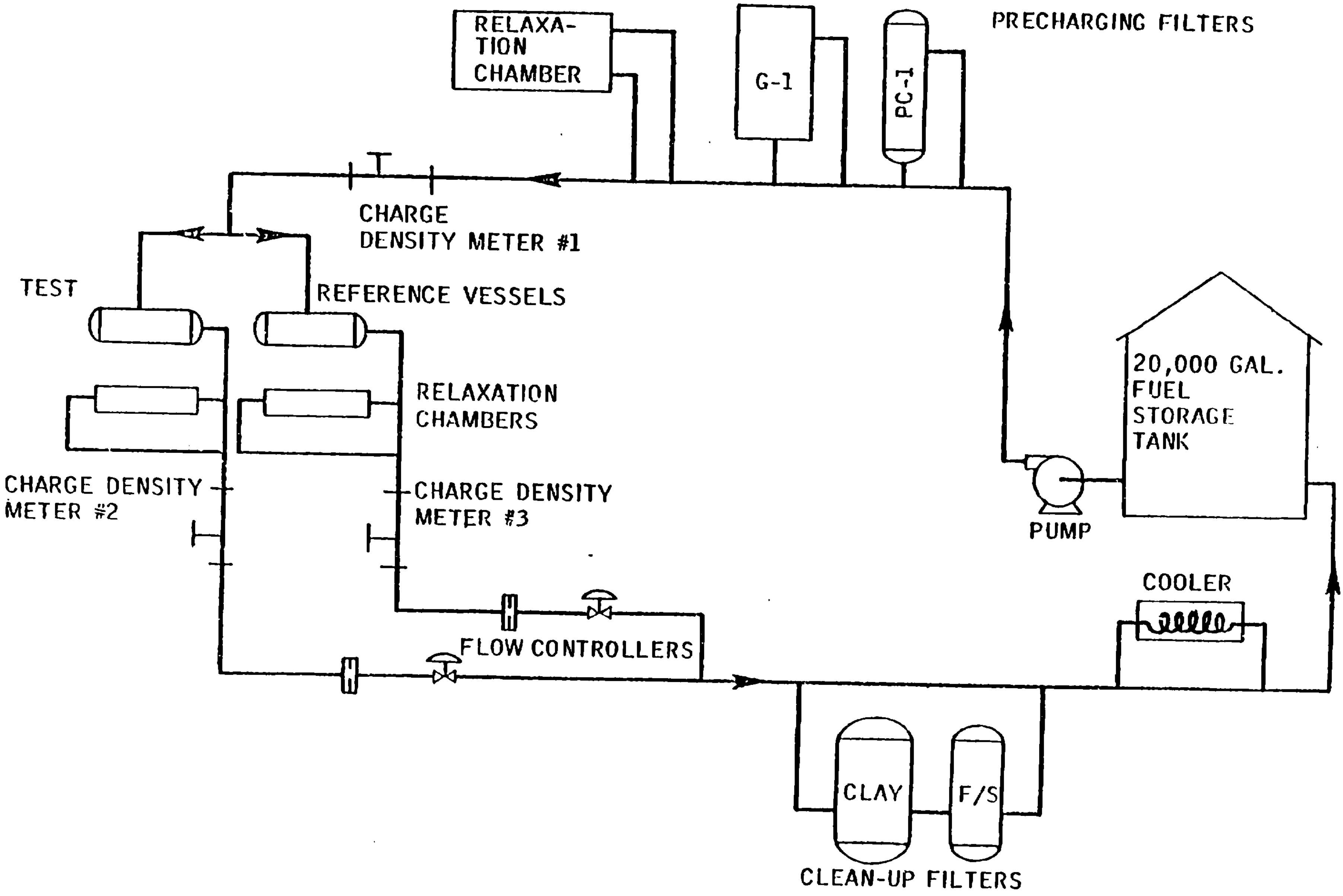
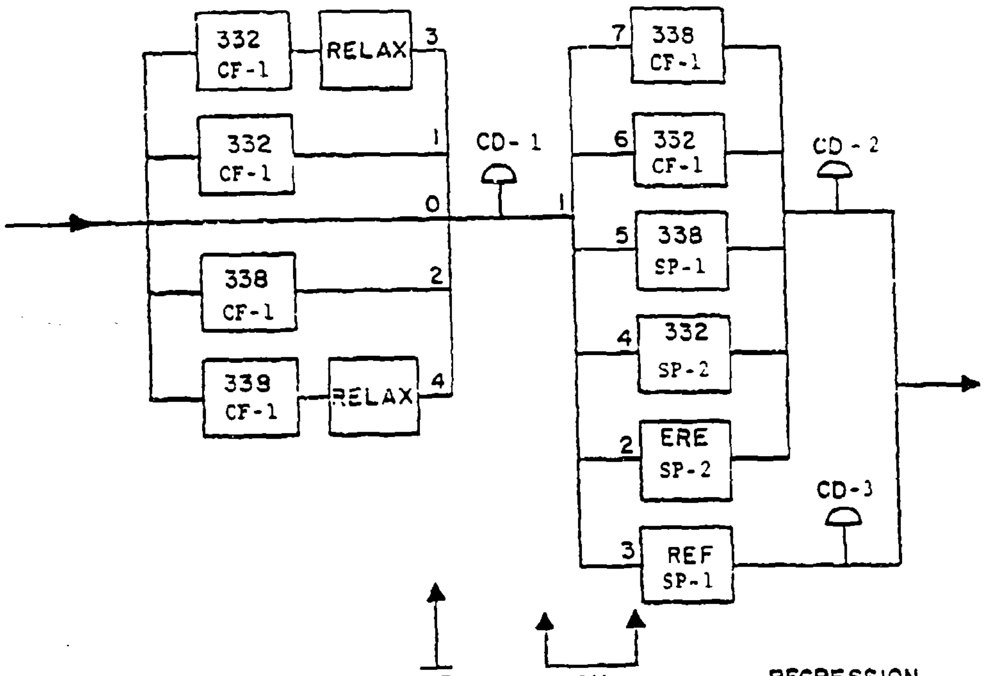


FIGURE 3-2

SYSTEM ANALYSES



	PF	SY	REGRESSION ANALYSIS
SC VS CD (X) (Y)	1	1	✓
	2	1	
	0	2	✓
	0	3	
	0	4	
	0	5	
	0	6	
	0	7	
SC VS CD − CD_1(AVE) (X) (Y)	0	2	✓
	0	3	
	0	4	
	0	5	
	0	6	
	0	7	
	1	3	
	1	4	
	2	3	
	2	5	
	3	3	
	3	4	
	4	3	
	4	5	

FIGURE 3-3

EFFECT OF FUEL TEMPERATURE ON FILTER CHARGING
FUEL MOISTURE CONTENT CONSTANT (~25 ppm V)

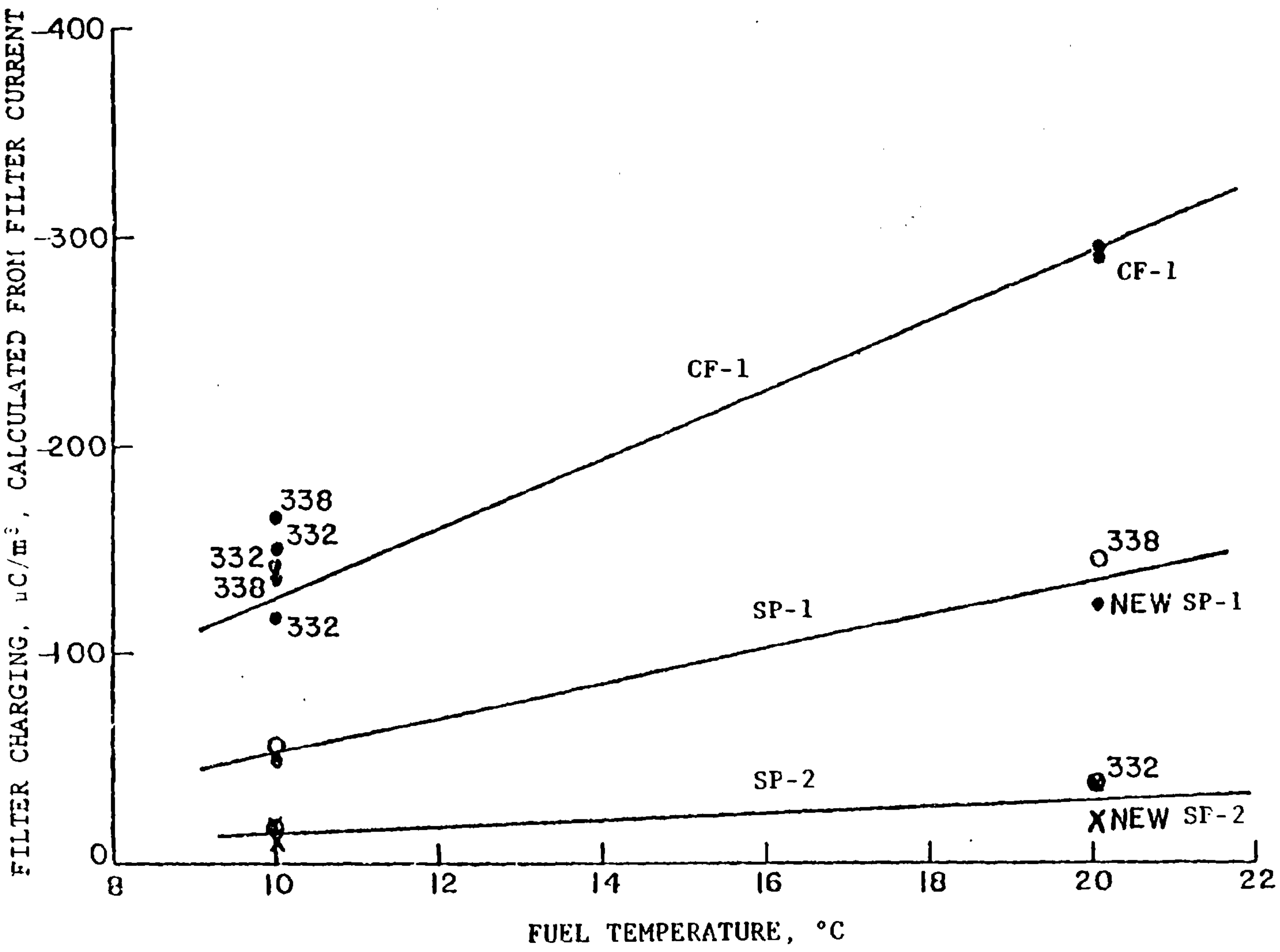


FIGURE 3-4

EFFECT OF DISSOLVED WATER ON FILTER CHARGING LEVEL

FUEL HELD AT CONSTANT TEMPERATURE OF 10°C

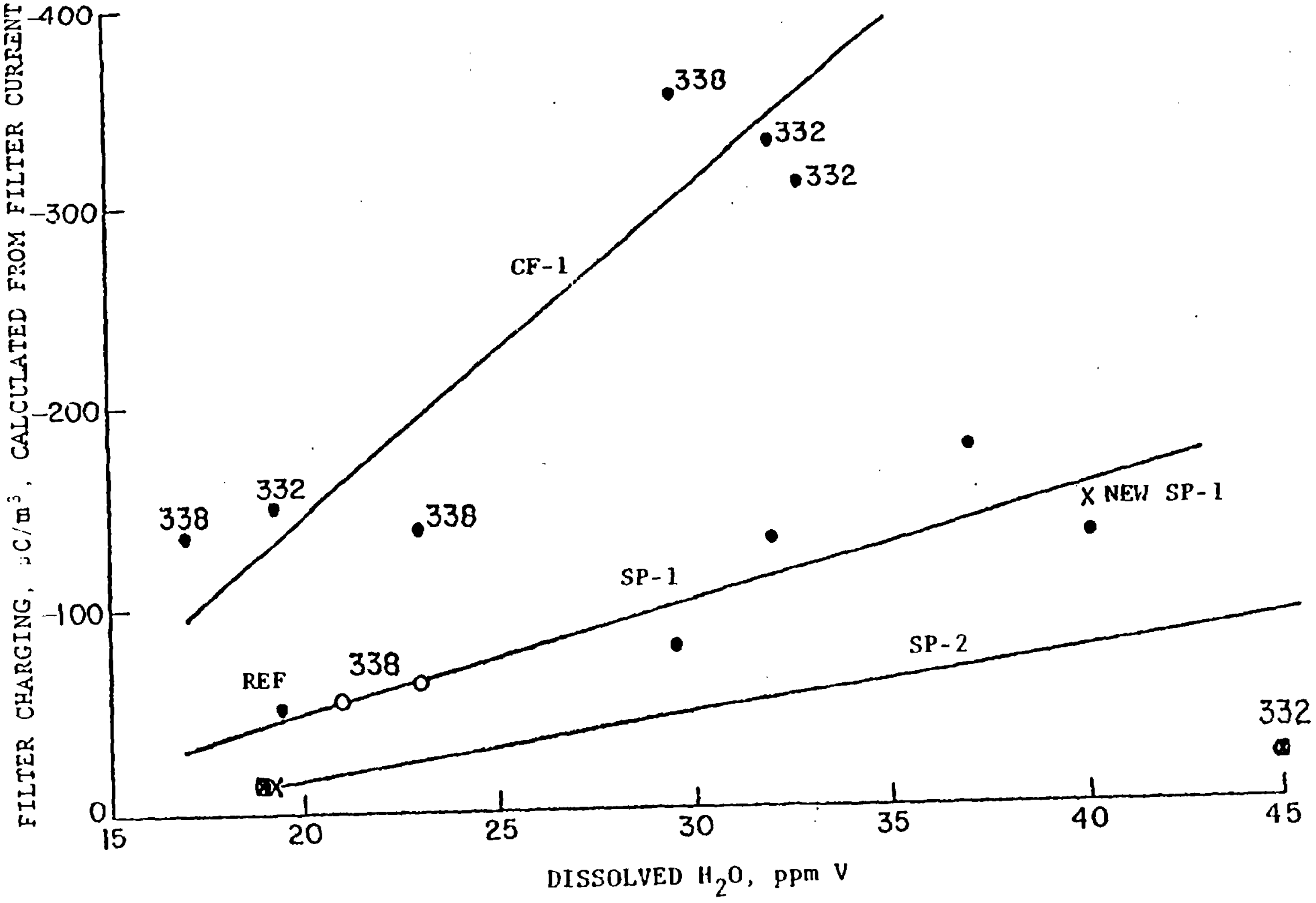


FIGURE 3-5

MEASURED VERSUS CALCULATED CHARGE DENSITY

TEST SEQUENCE 1

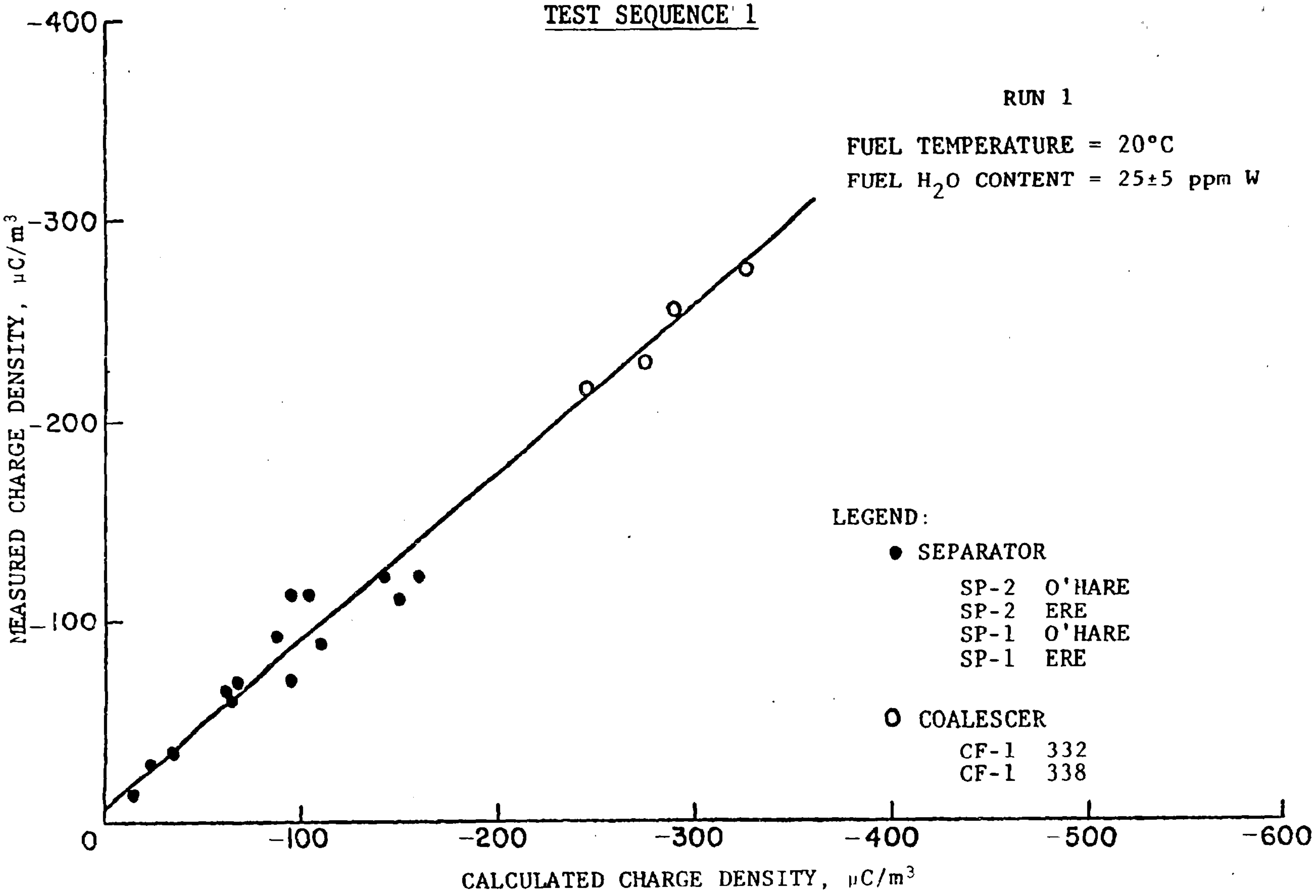
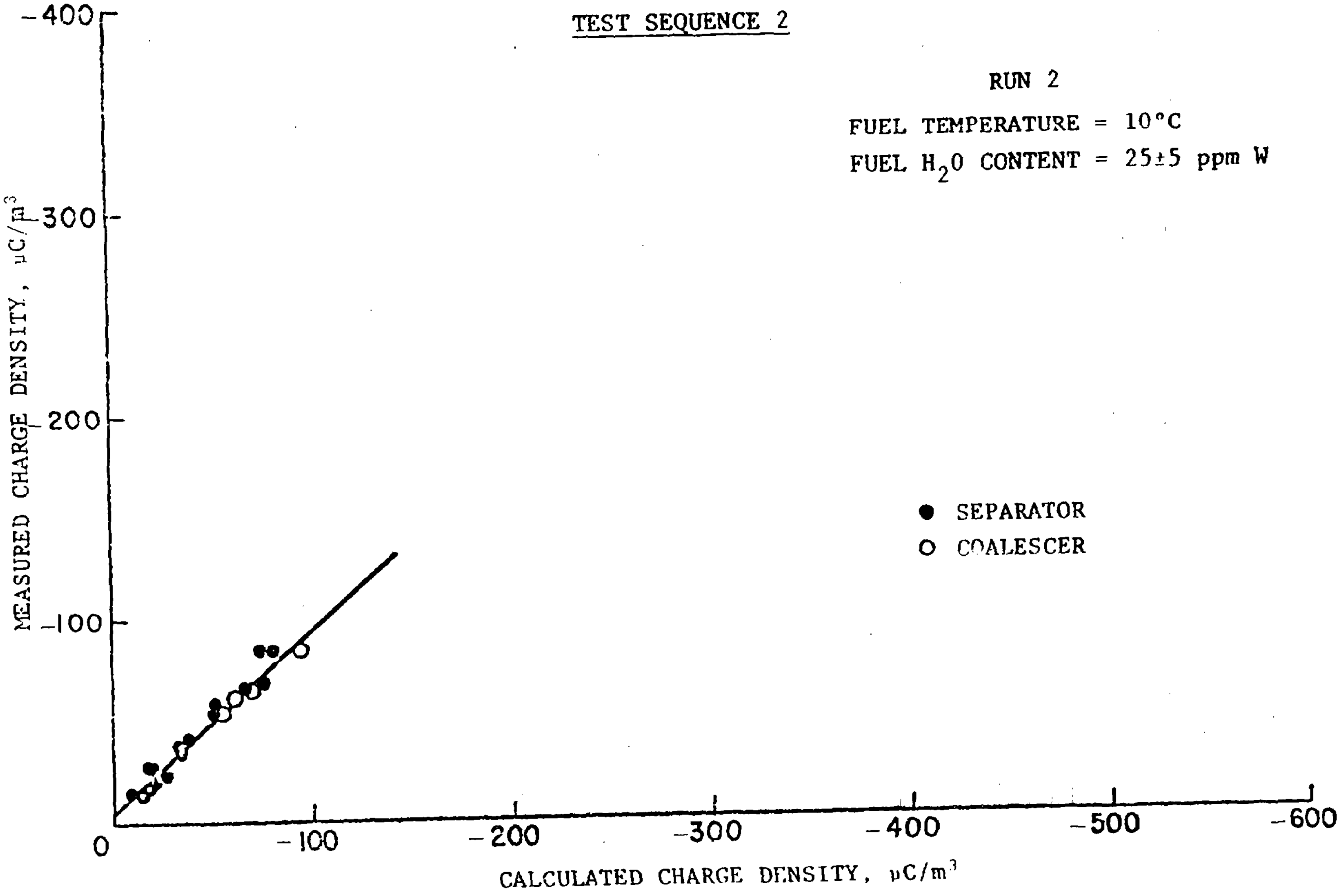


FIGURE 3-6

MEASURED VERSUS CALCULATED CHARGE DENSITY

TEST SEQUENCE 2



RUN 2

FUEL TEMPERATURE = 10°C

FUEL H_2O CONTENT = 25±5 ppm W

FIGURE 3-7

MEASURED VERSUS CALCULATED CHARGE DENSITY

TEST SEQUENCE 3

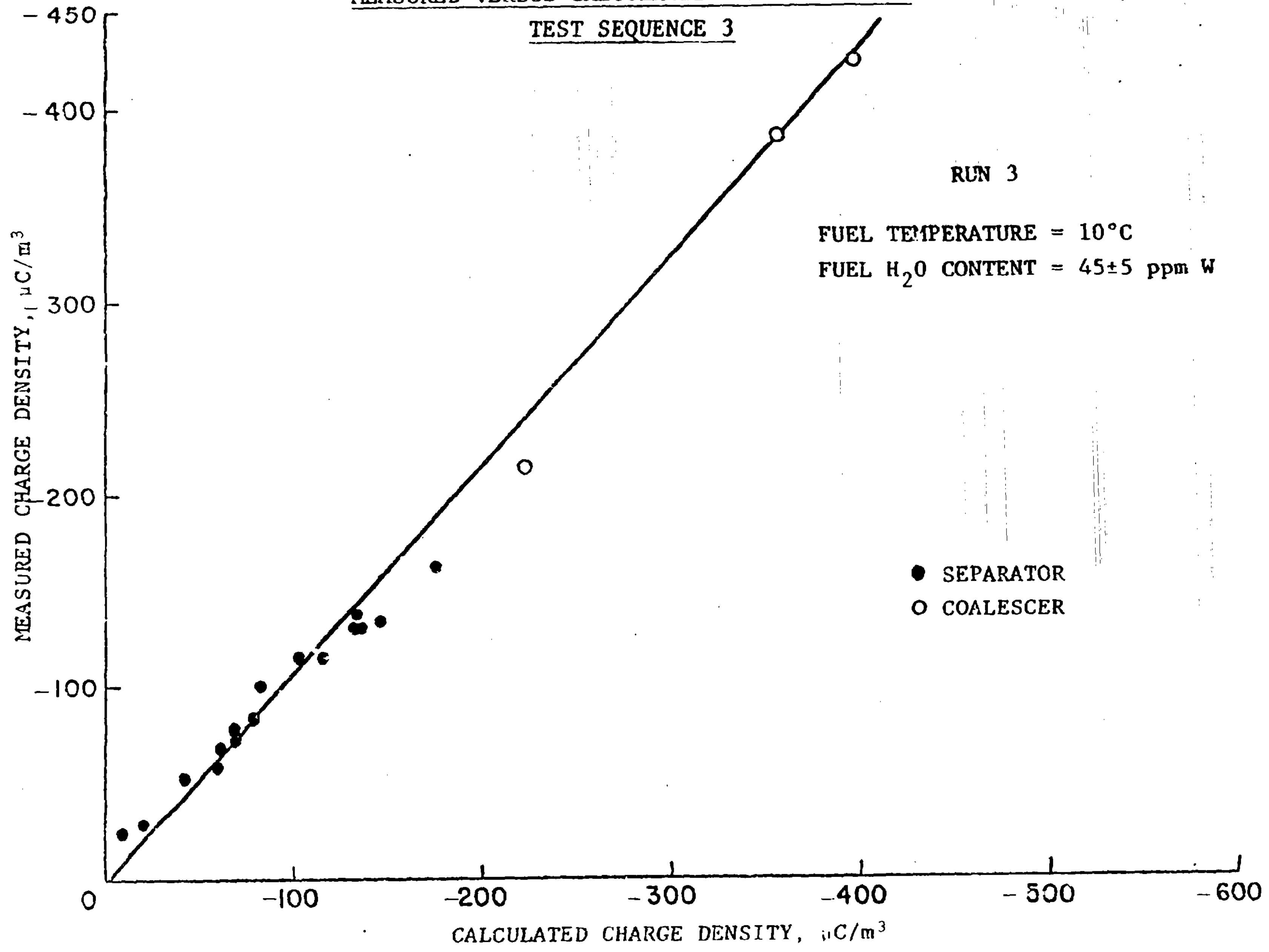
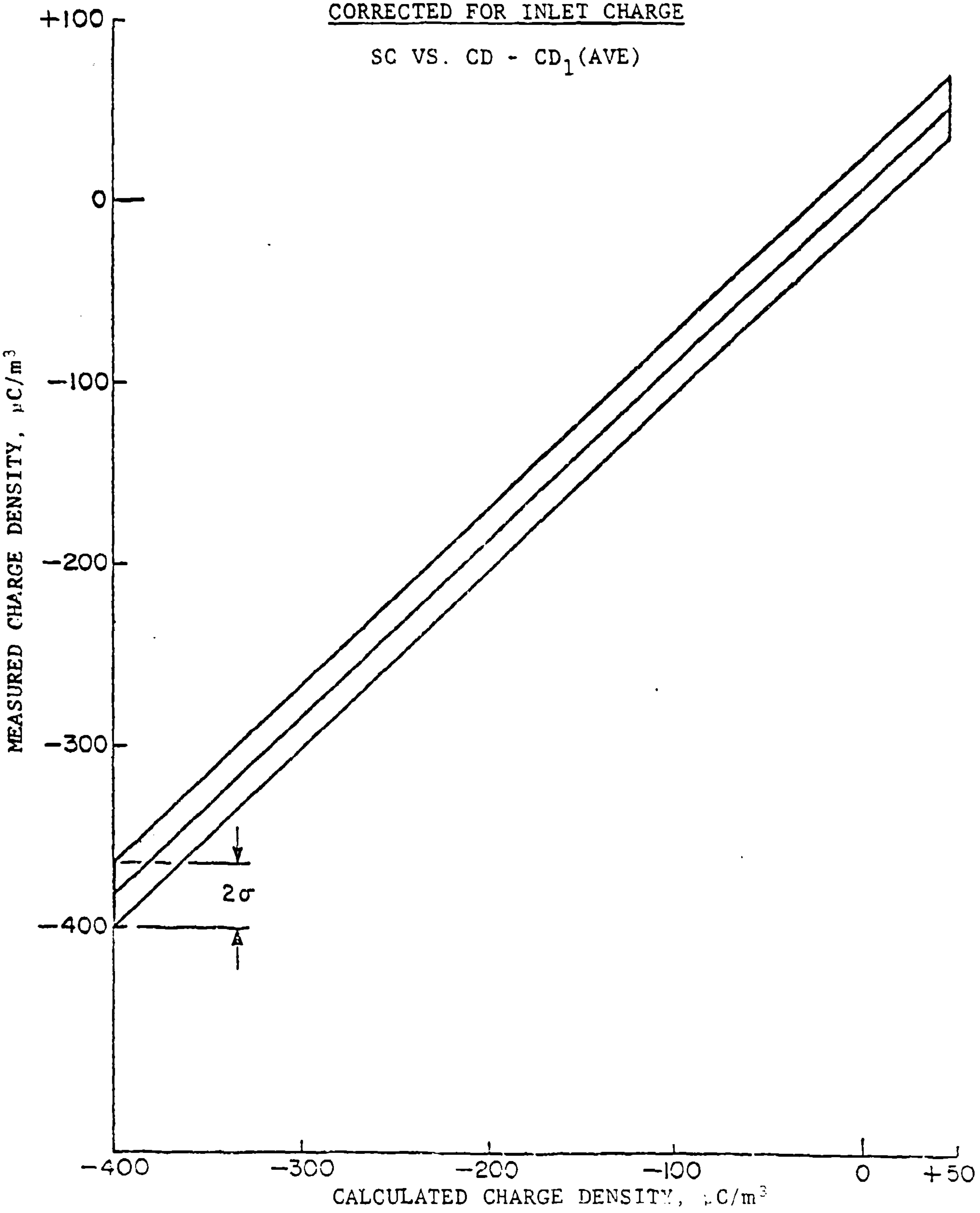


FIGURE 3-8

CORRELATION OF MEASURED VS. CALCULATED CHARGE DENSITY CORRECTED FOR INLET CHARGE

SC VS. CD - CD_1(AVE)



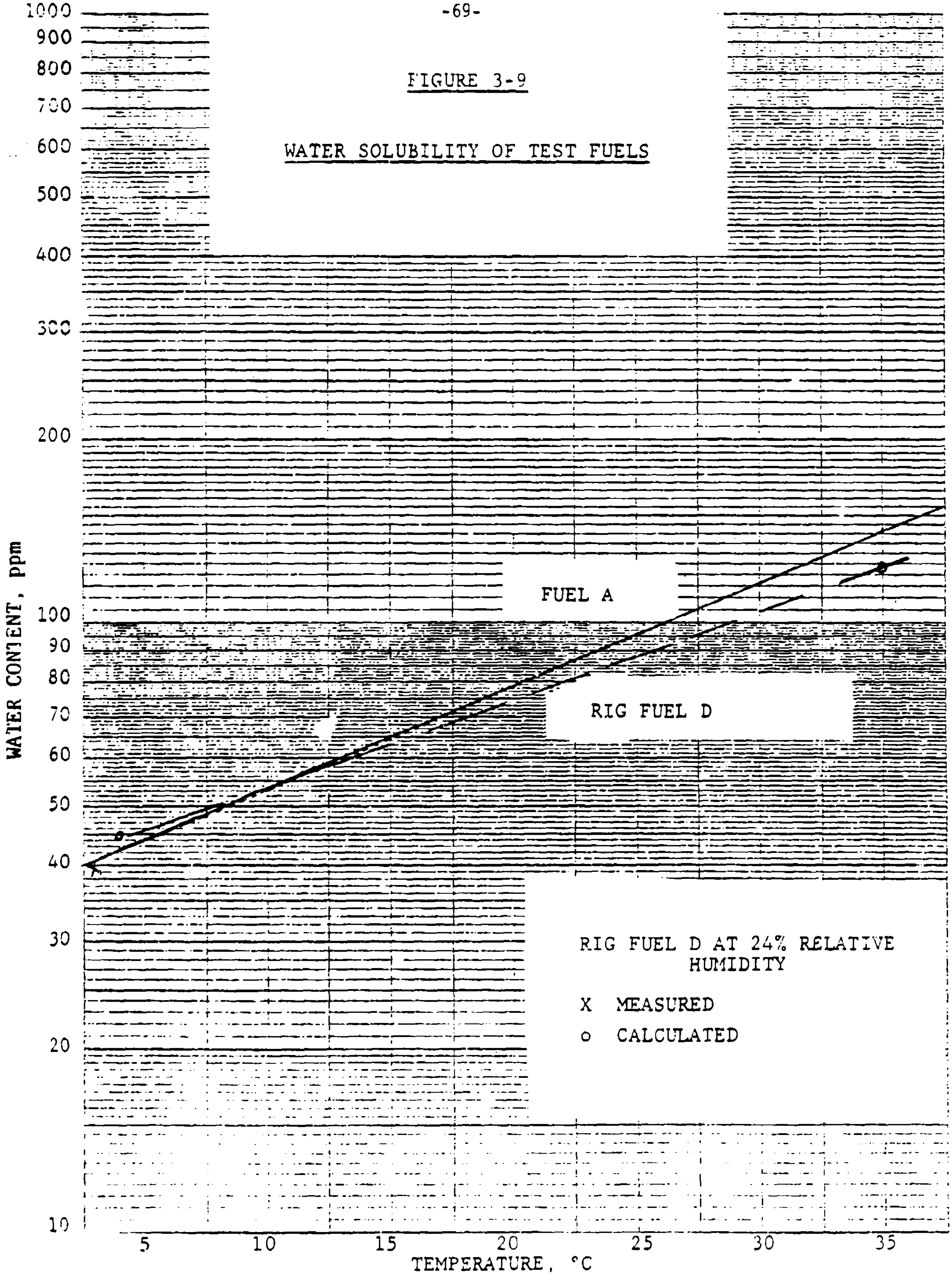


FIGURE 3-9

WATER SOLUBILITY OF TEST FUELS

REFERENCES

REFERENCES

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2. Coordinating Research Council, Inc., "Electrostatic Charging Characteristics of Jet Fuel Filtration Equipment," CRC Report No. 458, June 1973.

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5. D. A. Young and W. G. Dukek, "Electrostatic Charging Test for Aviation Fuel Filters," CRC Project No. CA-53-75 (Contract USA DAA05-68-C-0068), June 1977.

APPENDIX A

MEMBERSHIP:

CRC AVIATION GROUP ON FILTER CHARGING CHARACTERISTICS FIELD TEST PANEL

MEMBERSHIP:

CRC AVIATION GROUP ON FILTER CHARGING CHARACTERISTICS

FIELD TEST PANEL

R. T. Holmes, Leader	Shell Oil Company
P. P. Campbell	United Air Lines
W. G. Dukek	Exxon Research and Engineering Company
I. Ginsburgh	Amoco Oil Company
D. L. Rhynard(1)	Mobil Research and Development Corporation
J. G. Scheltens	Lockheed Air Terminal, Inc.
J. J. Shea	Federal Aviation Administration
K. H. Strauss	Texaco Inc.
D. A. Young(2)	Exxon Research and Engineering Company

Additional Participants

H. G. J. Meyers	Amoco Oil Company
R. Haefer	Lockheed Air Terminal, Inc.

---

(1) Replaced by P. W. Kirklin, Mobil Research and Engineering, April 1978.

(2) Contract Program Coordinator.

APPENDIX B

CALCULATION TECHNIQUE FOR ESTIMATING CHARGING LEVELS OF FILTER ELEMENTS

CALCULATION TECHNIQUE FOR ESTIMATING CHARGING LEVELS OF FILTER ELEMENTS

A charged hydrocarbon liquid loses its charge by flow of electrical current within the liquid to a boundary, a process called charge relaxation or charge decay. In theory, the rate of charge relaxation is proportional to the product of conductivity and charge density. In practice, charge relaxation is sometimes observed to occur at a rate different than that implied by measured or rest conductivity. This discrepancy has led to the practice of ascribing "effective conductivity" in a flowing hydrocarbon liquid to match the observed relaxation rate.

The discrepancy is important for low-conductivity liquids (i.e., under 1 pS/m) in which the observed relaxation of highly charged fuel is faster than rest conductivity would predict. For most fuels in which rest conductivity adequately characterizes charge relaxation rate, the formula for predicting charge as a function of time for unvarying conductivity is:

$$Q = Qi\ e^{\frac{-tK}{\varepsilon}} \qquad \text{(B-1)}$$

where:

Q = charge density (coulomb/meter^3)

Qi = initial charge density (coulomb/meter^3)

K = conductivity (siemen/meter)

t = time (second)

ε = dielectric permittivity of the liquid (farad per meter)

e = base of Naperian logarithm (2.718)

The dielectric permittivity of free space is 8.84 picofarad/meter, and of hydrocarbon fuels about 2 pF/m. Substituting into Equation B-1 and taking the logarithm produces the relationship:

$$\ell n \text{ (residual fraction of initial charge)} = \frac{Kt}{17.7}$$

It is apparent that conductivity K expressed as picosiemens per meter is the slope of a straight line in a plot of logarithm of fractional charge versus time in seconds.

Because charge is measured in flowing fuel at a downstream point (the CDM), the upstream charge at any point can be calculated from this semilog relationship with time, if both conductivity of fuel and residence time are known.

Residence time is determined by the volume within the filter/separator case on the cart. About 70 percent of the case volume is between the coalescer and separator, 15 percent is downstream of the separator, and units with hydraulic lift decks provide an extra 20 gallons in piping and line. In Table B-1, the values within those carts have been translated into residence time in seconds for fuel flowing at different rates.

In field charging tests at O'Hare Airport, rest conductivity was not measured in the field, but effective conductivity was calculated by observing the rate for 50 percent of the equilibrium charge to relax when flow stopped. At best, this calculation is a rough average, for it assumes constant conductivity, when in fact the decay rate is usually initially very rapid and then tapers off. In the case of all three test fuels in the field, the time for 50 percent charge decay suggested average effective conductivities below 1 pS/m. Data obtained in the 1961 CRC Phase II program*, however, revealed that charge relaxation (as a measure of effective conductivity) is higher than rest conductivity below 1 pS/m, but lower than rest conductivity above 1 pS/m. Figure B-1 reproduced from the CRC report illustrates this point. The rest conductivities measured on field fuels in the laboratory varied from 0.69 to 2 pS/m. The ratio of effective to rest conductivities for Fuels A, B, and C suggest a behavior similar to the lower curve of Figure B-1.

Figure B-2 is a semilog plot of fraction of charge against time in seconds for conductivities ranging from 0.11 to 2 pS/m. The three linear plots shown dashed represent the effective conductivities calculated in the field for Fuels C, B, and A, respectively, while the bottom solid linear plots represent the rest conductivities measured for these fuels. On the abcissa of Figure B-2, residence times for hydrant carts at different flow rates are shown. When Figure B-2 is used to back-calculate the charge produced at the separator or coalescer, the slope (conductivity) of the line is obviously critical.

The 1961 CRC data showing that fuels with rest conductivities below 1 pS/m generally relaxed much faster than predicted was explained and demonstrated by Bustin in 1964**. He showed that relaxation rates with fuels containing very few charge carriers (i.e., low conductivity) were hyperbolic rather than exponential and that the charge density followed the formula:

$$Q = \frac{Qi}{1 + mQi\,\frac{t}{\varepsilon}} \qquad \text{(B-2)}$$

---

* Coordinating Research Council, Inc., "Electrostatic Discharge in Aircraft Fuel Systems - Phase II," CRC Report No. 355, 1961.

** W. M. Bustin, J. Koszman, and I. T. Tobye, "New Theory for Static Relaxation from High Resistivity Fuel," API Division of Refining Proceedings 44 (III), 548-561, 1964.

Relaxation rate is proportional to charge squared instead of its first power. It is dependent upon m, the mobility of charge carriers, and on the charge density. At high charge levels, the relaxation rate can be quite rapid. The apparent mobility m of charged particles is about 10^{-8} meter^2 per volt-second. Typical data from Bustin are as follows:

Rest Conductivity pS/m	Initial Charge Density $\mu C/m^3$	% Left After 30 Seconds	% Expected Based on Conductivity
0.13	65	33	82
0.25	253	28	69
2.07	332	10	4.5

The first two sets of data imply that remaining charge after 30 seconds is only 40 percent as high as would be predicted from rest conductivity. Thus, if the rest conductivity of Fuels C and B are really 0.11 and 0.24 pS/m, as calculated from charge decay, the relaxation formula of Equation B-2 should be used.

Hyperbolic charge decay curves of Equation B-2 are plotted in Figure B-3 for two assumed ion mobilities (0.3 x 10^{-8} and 1.0 x $10^{-8}m^2/v\text{-}s$) at initial charge density levels of 10, 30, 100, and 300 $\mu C/m^3$. At the lower value of ion mobility, the decay curves resemble the exponential decay curves of Figure B-2, but the slope (i.e., conductivity) increases with the charge density. At the higher value of ion mobility, the decay curves appear exponential only at low charge densities. Back-calculating the charge of coalescers and separators from downstream charge density readings when hyperbolic decay takes place is difficult, but Figure B-3 makes a graphical solution possible.

To illustrate the application of these charge decay equations and figures by examples, consider first the data from Cart E-338 in Test Period C. Fuel A exhibited an effective conductivity of 0.54 pS/m (and a rest conductivity of 2 pS/m in the laboratory), and one would expect exponential charge decay. At 13 seconds after start, a peak charge of -240 $\mu C/m^3$ was recorded by the CDM. From the line of slope 0.54 pS/m of Figure B-2, the charge remaining after 13 seconds would be a 0.68 fraction of the initial charge, which is then calculated as -240/0.68 = -353 $\mu C/m^3$ at Separator SP-1. A second peak of -84 $\mu C/m^3$ recorded 11 seconds later (24 seconds after start) represents the combined charge of both separator and coalescer at the charge density meter. From Figure B-2, the net charge at Separator SP-1 after 24 seconds is calculated as -84/0.49 = -171 $\mu C/m^3$ significantly lower than the initial value. The difference in these two calculated values for charge at the separator represents the positive charge contributed by the coalescer. Using Figure B-2 for the 11-second interval between these two peaks, one back-calculates the coalescer charge as (353-171)/.73 = 182/0.73 = +250 $\mu C/m^3$.

An example of hyperbolic charge decay best handled by a graphical solution are the data from Cart E-313 in Test Period C. Fuel B exhibited an effective conductivity of about 0.24 pS/m. At 10 seconds after start, a peak charge of -13 $\mu C/m^3$ was recorded by the CDM. Using the lines in Figure B-3 for an ion mobility of 10^{-8} m^2/v-s, a charge density point plotted at 10 seconds on a line of slope midway between the charge decay lines at 10 and 30 initial charge densities would produce an estimated Separator SP-1 charge at time zero of -15 $\mu C/m^3$. A second peak of -4 $\mu C/m^3$ was recorded 11 seconds later, representing the combined charge of both elements. Following a similar procedure for a charge density point plotted at 21 seconds, one estimates a new charge of -4.5 $\mu C/m^3$ at the separator. The difference of +10.5 $\mu C/m^3$ represents the coalescer's contribution. Again following the graphical procedure by plotting the 10.5 value of 11 seconds, oneestimates the coalescer's contributions to be +12 $\mu C/m^3$ at time zero.

In deciding what type of charge decay prevailed, judgment must be exercised. For example, in Test Period D, Fuel B exhibited a very low effective conductivity (long time for 50 percent decay) when Cart E-348 was tested, but had increased in conductivity (shorter time for 50 percent decay) when Cart E-313 was tested. These results suggest that ohmic decay is a much more likely relaxation path.

TABLE B-1

HYDRANT CART FUEL VOLUMES

ASSUMPTIONS:

(1) 70 percent of the filter/coalescer (F/S) case volume is located between the separator and coalescer.

(2) 15 percent of the F/S case volume is downstream of the separator elements.

(3) Units equipped with hydraulic lift decks have an additional 20 gallons of fuel in the extra piping and hoses.

Using the hydrant cart and test manifold dimensions shown in Figures 2-2 and 2-4, the approximate downstream fuel volumes from the coalescer and separator elements are as follows:

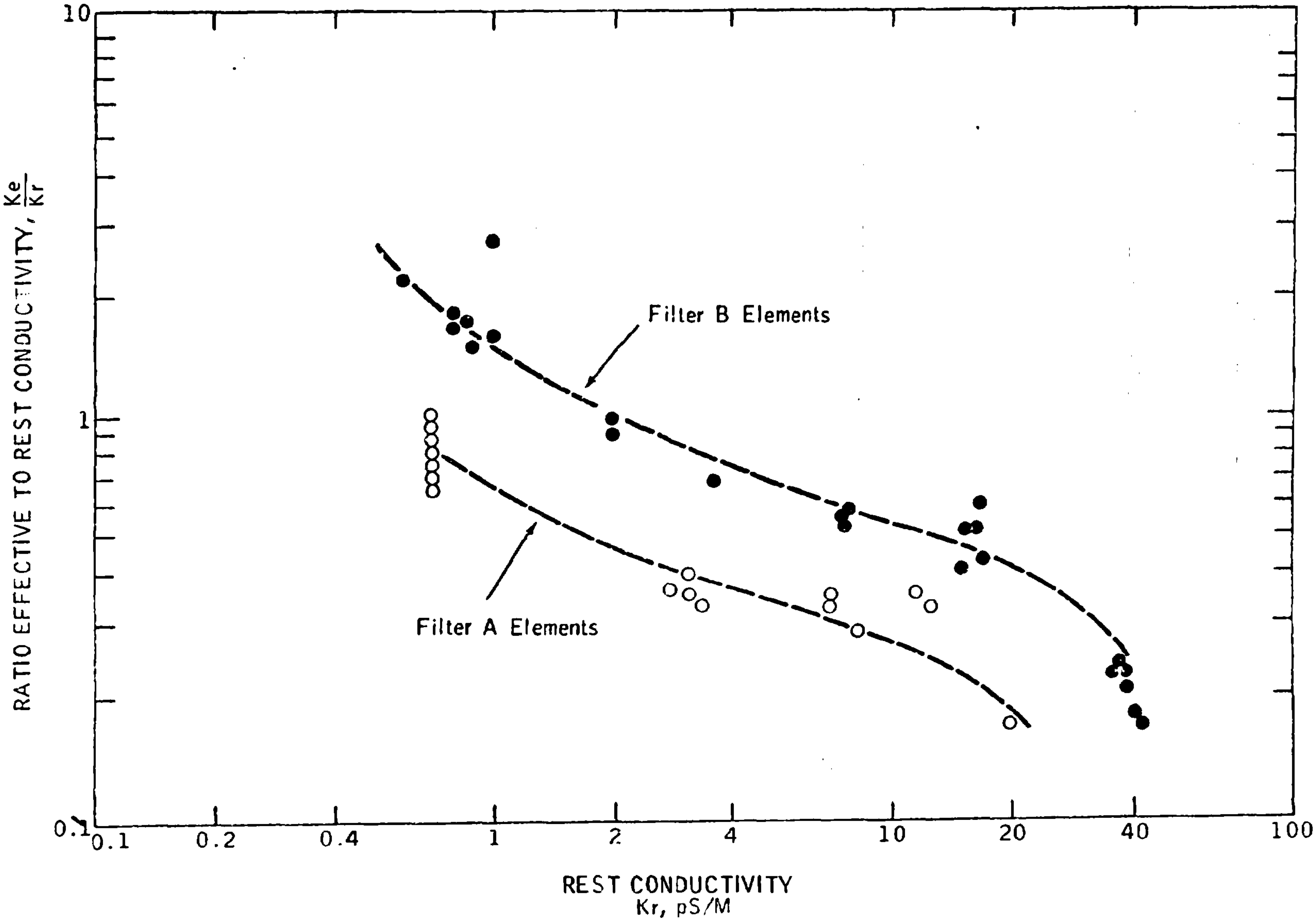
Between coalescer and separator elements: 70 percent of case volume	137.0 gallons
Separator element to charge density meter: 15 percent of case volume	29.4 gallons
line, hose, and manifold volume to CDM	49.4 gallons
	78.8 gallons
Hydraulic lift - all 20 gallons:	20.0 gallons
	98.8 gallons

RELAXATION TIME, SECONDS

	250 gpm	600 gpm
Coalescer to Separator (137 gallons)	32.9	13.7
Separator to CDM - without hydraulic lift (78.8 gallons)	18.9	7.9
Separator to CDM - with hydraulic lift (98.8 gallons)	23.7	9.9
Coalescer to CDM - without hydraulic lift (215.8 gallons)	51.8	21.6
Coalescer to CDM - with hydraulic lift (235.8 gallons)	56.6	23.6

FIGURE B-1

EFFECTIVE VERSUS REST CONDUCTIVITY



Note: Reproduced from Figure 23 of Reference 5.

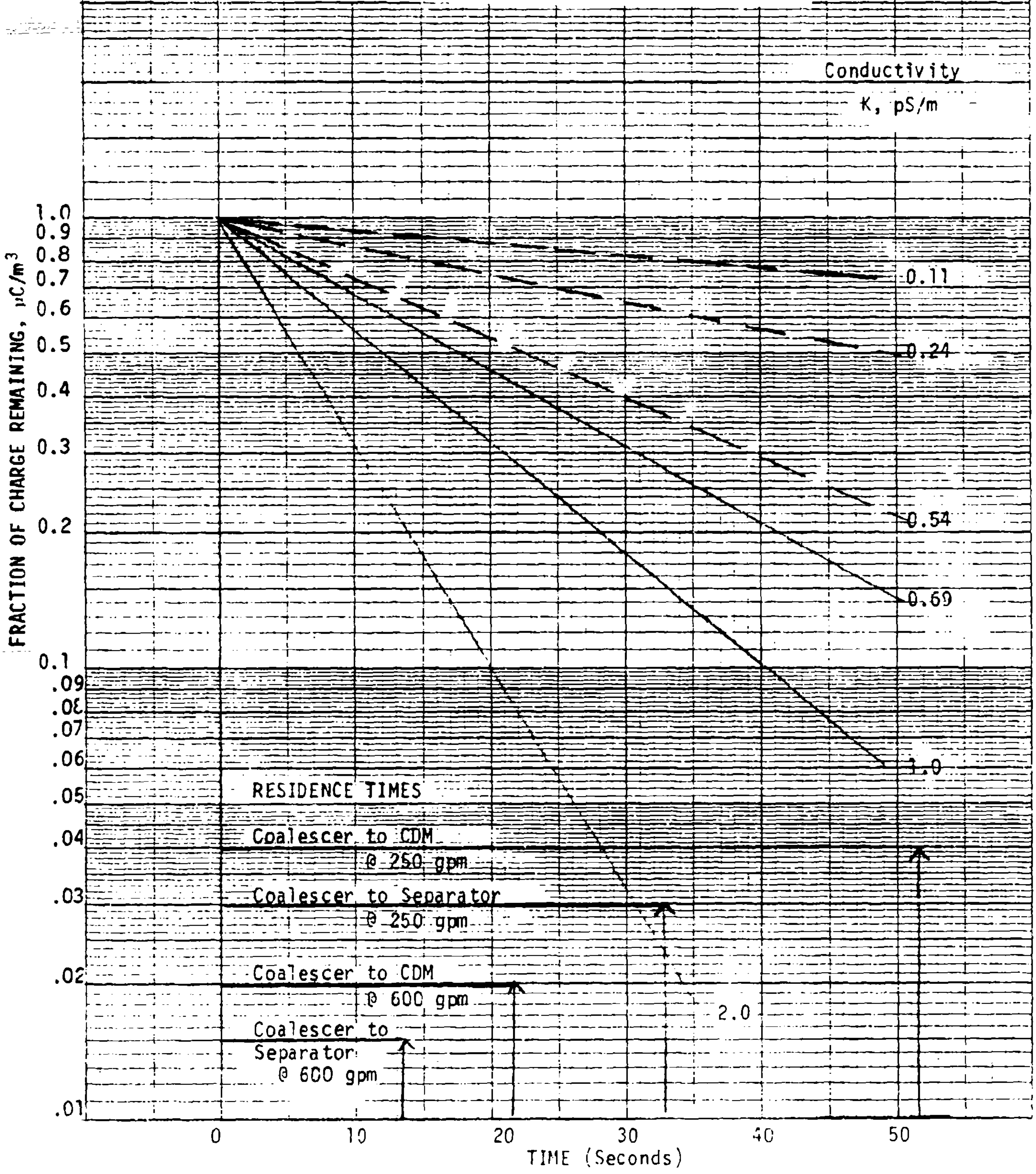
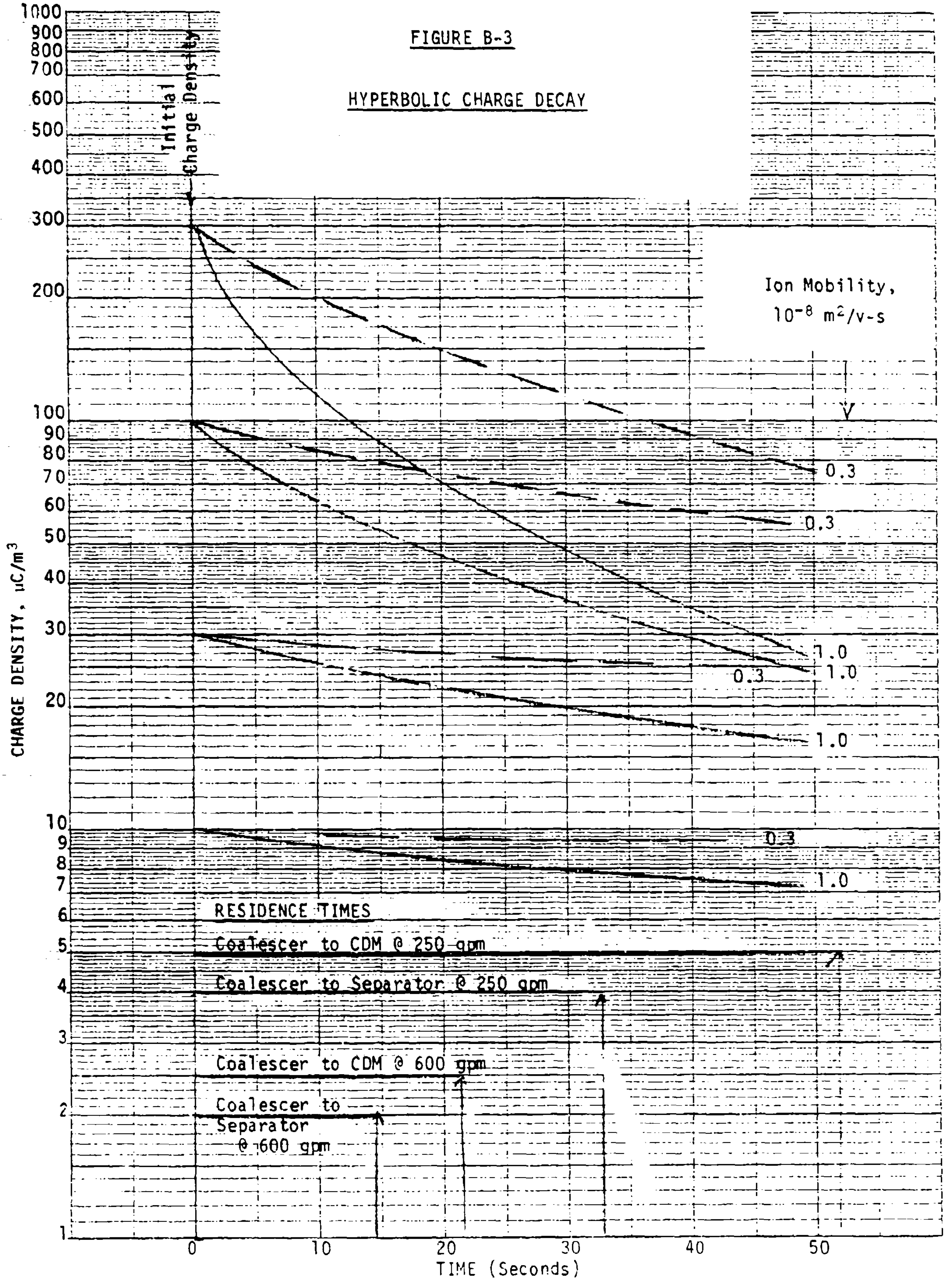


FIGURE B-2

EXPONENTIAL CHARGE DECAY

FIGURE B-3

HYPERBOLIC CHARGE DECAY



APPENDIX C

AVIATION FUEL FILTER ELECTRICAL CHARGING TEST

AVIATION FUEL FILTER ELECTRICAL CHARGING TEST

1. SCOPE

1.1 This method consists of test rig and laboratory procedures for measuring the relative static charge generating characteristics of filter media exposed to flowing aviation fuel.

2. SUMMARY OF METHOD

2.1 Static charge generated by the flow of fuel through a filter media is caused by ionic species which separate charge on the filter surface. The quantity of charge separated is measured by the current that flows to earth from the electrically isolated filter under specified conditions of flow. For testing filter media in the form of single elements of the type used in field installations, the method describes a test rig (Part A) consisting of two test sections in parallel, one of which is used for a reference filter element. Aviation fuel controlled in terms of purity, temperature and dissolved water content is pumped at rated flow through both test sections simultaneously and the charging tendency of a filter media relative to a reference media is measured. The temperature and water response of the filter media is determined by controlling these variables in the test fuel. In a laboratory test device (Part B), a section of filter media is tested under standardized flow conditions with fuel controlled in purity, temperature, water content and content of pro-static additive. The charging tendency of filter media relative to a reference media tested in the laboratory device is then compared with the single element results of Part A to extend the estimates of field performance of filters.

3. SIGNIFICANCE AND USE

Filter media can differ significantly in their static charging tendency due to design and materials of construction. Tests of single elements of the type which are used as multiples in field installations provides a basis for selecting the preferred filter coalescers and separators for use with aviation fuel. Rig testing filters with well controlled fuel supplemented by laboratory testing of filter media provides a basis for estimating the field performance of filter elements.

4. PART A : TEST RIG PROCEDURE

4.1 Apparatus

4.1.1 The proposed test rig is described in schematic terms in Figure D-1 and consists of a fuel supply system, test sections and measurement systems.

4.1.2 A fuel supply system consists of an insulated storage tank holding at least 20 times the maximum volume output of the pump per minute, a pump capable of delivering the rated flow of both test sections simultaneously at proper pressure, two independent flow controllers for each test section, a cooler capable of reducing the temperature of fuel at least 10°C and full-scale clean-up clay filters and filter-separators for removing contaminants from fuel. The ullage space of the storage tank should be protected against the atmosphere in order to maintain constant the water content of the fuel. Dry nitrogen injection should be provided in the return line to the storage tank in order to purge water from the fuel. Provision should be made for sampling fuel and for injecting water and additives at the pump inlet. A temperature probe is needed in the fuel line ahead of the test sections.

4.1.3 Test sections consist of two filter vessels sized to install a single filter element of either a coalescer or separator type. Both filter vessels are installed to be electrically isolated from earth at the fuel inlet, fuel outlet, and supporting structure.

4.1.4 Filter charge is measured by installing a Keithley Electrometer between ground and the filter case. The output of the Electrometers can be observed or recorded. Output of the flow controllers and temperature gage may also be recorded.

4.2 Test Fuel and Conditioning

4.2.1 Jet A fuel to the ASTM D 1655 specification is used as the test fluid.

4.2.2 The fuel is conditioned prior to test by recirculating through the test rig and the clean-up clay filter and filter-separator. Dry nitrogen is introduced in the inlet line to the storage tank. Fuel samples are taken periodically for testing.

4.2.2.1 Fuel should be circulated until the electrical conductivity by ASTM D 3114 shows a value below 1 pS/m and the dissolved water content by ASTM D 1744 or its equivalent is between 20-30 ppm at 20°C.

NOTE 1: Recirculation also serves to clean the test system of contaminants that could affect fuel conductivity.

4.3 Reference and Test Filter Elements

4.3.1 After the fuel is conditioned, a reference filter element is installed in one test section and a test filter element is installed in the parallel test section.

4.3.2 Reference and test elements are conditioned by recirculating fuel through them at controlled rated flow for four hours. Filter current readings on the Electrometers or the recorder are observed to determine when equilibrium is reached. The four-hour recirculation period serves as a "break-in" or conditioning period.

4.3.3 In subsequent testing the flow controllers should be adjusted so that flow rate through the reference filter matches flow rate through the test filter.

4.4 Test Procedure Sequence

4.4.1 The first test sequence consists of measurements at temperature T ±1°C with a total water content of 25 ±5 ppm. Recirculation at rated flow through each test section continues until equilibrium values are noted over a two hour period. Average three readings.

NOTE 2: At a temperature of 20°C, a water level of 25 ppm represents about 35% of saturation.

4.4.2 In the second test sequence the cooler is operated to lower the temperature to T-10°C ±1°C maintaining the total water content at 25 ±5 ppm. Recirculation at rated flow through each test section continues until equilibrium values are noted over a two hour period. Average three readings.

NOTE 3: At a temperature of 10°C, a water level of 25 ppm represents about 50% of saturation.

4.4.3 In the third test sequence, the fuel temperature is maintained at T-10°C ±1°C but the total water content is raised to 45 ±5 ppm by injecting water into the inlet of the pump. Recirculation at rated flow through each test section continues until equilibrium values are noted over a two hour period. Average three readings.

NOTE 4: At a temperature of 10°C, a water level of 45 ppm represents about 80% of saturation.

4.5 Calculation of Results

4.5.1 The charge density (CD) of both reference and test filters are calculated from filter current as follows:

$$\text{CD, } \mu\text{C/m}^3 = \frac{\text{Filter current in } \mu\text{A}}{\text{Flow rate through filter, m}^3\text{/S}}$$

4.5.2 The relative charging tendency of test filters are determined for each test sequence by dividing the CD of test filter by the CD of the reference filter.

5. PART B - LABORATORY TEST PROCEDURE

5.1 Apparatus

5.1.1 The Mini-Static Charging Tendency Test (MST) Apparatus and Procedure are described in Appendix D of CRC Report 478 "Survey of Electrical Conductivity and Charging Tendency Characteristics of Aircraft Turbine Fuels". A copy appears as Annex 1.

NOTE 5: Current procedure specifies a repeat run on the same filter media. With some fuels and media more repeats are needed to establish equilibrium because the media requires conditioning or "break in". The first values are discarded in developing an average result.

5.2 Preparation of Test Fuels

5.2.1 Clay Treated Fuel should be prepared by the procedure of Appendix A4 of D 2550 or sampled from the supply in the test rig (Part A).

5.2.2 Additive blends should be prepared using a concentrate of 1000 ppm of additive in clay treated Base Fuel blended with Base Fuel to specified levels, e.g., 20 and 100 ppm of pro-static agent.

NOTE 6: One or more pro-static additives can be used. The concentration should produce a conductivity less than 10 pS/m. GA178 is an example of such an additive.

5.2.3 Base Fuel and blends should be checked for conductivity by D 3114.

6. FILTER MEDIA

6.1 Samples of both reference and test filter media are obtained by cutting a 13 mm diameter section from a filter element.

NOTE 7: With fiberglass coalescers, larger diameter test sections may be necessary.

7. ENVIRONMENTAL CONDITIONING OF APPARATUS, TEST FUELS AND FILTER MEDIA

7.1 Tests at laboratory temperature, e.g., 20-23°C of fuels and media.

7.1.1 Testing at laboratory humidity.

7.1.1.1 Measure temperature and relative humidity

7.1.1.2 Open fuel sample to air, covering the opening with paper to keep out particulate, and condition apparatus, fuel and filter media for at least 24 hrs. before testing.

7.1.2 Testing at high relative humidity

7.1.2.1 Using a hood large enough to contain the fuel, test syringes and filter media, establish a water train to deliver saturated air as is or mixed with laboratory air. Measure relative humidity within the hood.

7.1.2.2 Condition for at least 24 hrs. before testing.

7.1.2.3 For tests at humidity lower than laboratory level, substitute a stream of dry air for the water train.

NOTE 8: If the laboratory humidity is normally above 50% RH, tests under 7.1.1 should be made in a dry atmosphere, i.e., 25% RH.

7.2 Tests at elevated temperature, e.g., 30-33°C of fuels and media.

7.2.1 Establish apparatus and hood in a temperature controlled room (or large oven).

7.2.1.1 Measure temperature and relative humidity

7.2.1.2 As in 7.1.1.2 above, open fuel sample and conditioning fuel, media, etc. for 24 hrs. before testing.

7.2.2 Testing at high relative humidity

7.2.2.1 Operate the water train in the hood held at the elevated temperature of the room. Measure relative humidity.

7.2.2.2 As in 7.1.2.2 above, open fuel sample and condition fuel, media, etc. for 24 hrs. before testing.

NOTE 9: If the laboratory environment is normally at 30-33°C, tests under 7.2 should be run in a room cooled to 20-23°C, i.e., about 10°C lower than the base case.

8. PREPARATION OF WATER SATURATION CURVE FOR TEST FUEL

8.1 At <u>each test temperature</u>, saturate a separate fuel sample with water using a desiccator in which open fuel is exposed to a water saturated atmosphere for 24 hrs.

NOTE 9: A free water in the bottom of the fuel sample is inadequate and a wet blotter is undesirable.

8.2 Immediately test for total water by Method D 1744.

8.3 Plot measured water data as log (ppm water) vs. $\frac{1}{°K}$ to determine water saturation curve.

9. ANALYSIS OF TEST DATA

9.1 For each filter media and fuel combination, plot average MST CD values at constant water content against temperature. Crossplot average MST CD values at constant temperature against water content. (Absolute water content is determined by multiplying relative humidity times water saturation values, determined from the curve developed in para. 8.)

9.2 The relative charging tendency of test media is determined at each environmental condition by dividing the CD of test media by the CD of reference media.

10. CORRELATION OF TEST RIG AND LABORATORY RESULTS

10.1 The Part A and Part B CD Values for each media with base fuel are correlated after making suitable corrections for temperature and water level. This correlation relates the level of charge in the laboratory procedure to the level observed in the test rig.

10.2 The relative charging tendency for additive blends vs. base fuel blends in the Part B test is then determined and applied to the correlation of para. 10.1 to estimate the performance of both test and reference filter elements with a pro-static fuel.

FIGURE C-I

PROPOSED TEST RIG SCHEMATIC

AVIATION FUEL FILTER ELECTRICAL CHARGING TEST