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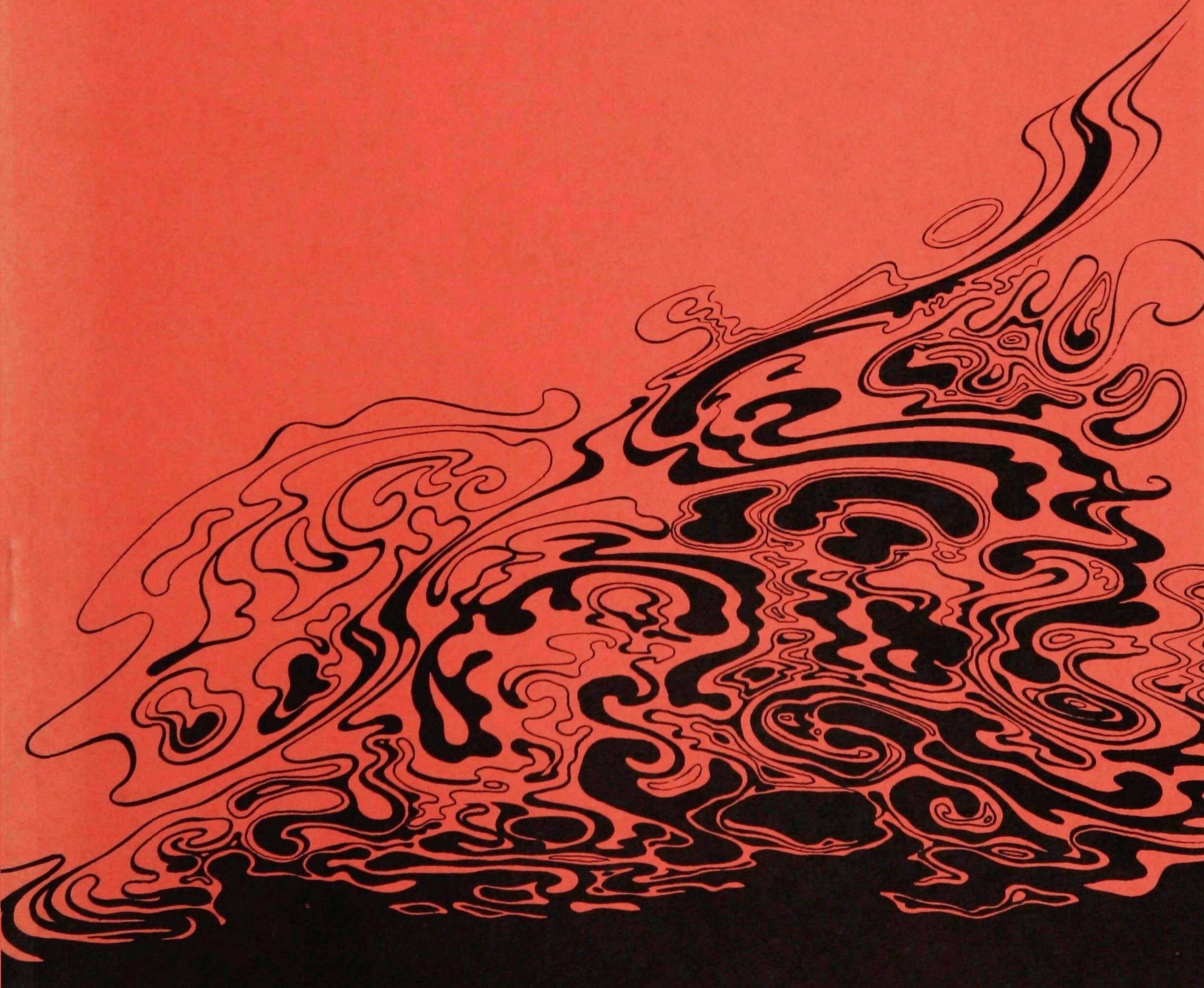
RECOVERY of FLOATING OIL ROTATING DISK TYPE SKIMMER



ENVIRONMENTAL PROTECTION AGENCY • WATER QUALITY OFFICE

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RECOVERY OF FLOATING OIL
ROTATING DISK TYPE SKIMMER

by

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for the

WATER QUALITY OFFICE

ENVIRONMENTAL PROTECTION AGENCY

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ABSTRACT

Laboratory tests of disc materials in oils ranging from light diesel to Bunker 'C' indicated that aluminum was the best overall. Experimental tests on model discs in still water established baseline performance data and understanding of scaling effects. Established that oil starvation between discs is a problem, but that percentage of water in recovered oil is less than 2% except for Bunker 'C'oil, and other oils in 2mm thickness slicks. Experimental tests of multiple discs in a towing basin established the effects of current and disc spacing, and showed that the rotational velocity vector in the fluid should be in the same direction as the current flow. Non-breaking waves have little effect on oil pick-up rate. The design method developed by comparison between theoretical analysis and experimental data shows that the overall size of the disc unit would be 7 ft. diameter by 12 ft. for recovery of 50,000 gallons per hour.

This report was submitted in fulfillment of Project Number 15080FWN, Contract 14-12-883, under the (partial) sponsorship of the Water Quality Office, Environmental Protection Agency.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

SECTION I

CONCLUSIONS

The most important conclusions resulting from this study are:

1. The recovery of 50,000 gallons of oil per hour using a series of powered disks is feasible and practical. The overall size of the disk unit is approximately 7 ft. diameter x 12 ft. long.

2. Disks can pick up oil spread as thinly as 1.5 mm in thickness. However, pickup efficiency and effectiveness is greatly improved with increased thickness. Refer to Figure 17, 23 and 32.

3. The disks can effectively be used for the pickup of light diesel as well as Bunker 'C' oil.

4. Disk pickup effectiveness is limited by starvation Starvation is the reduction of oil in the region adjacent to the disk due to insufficient feed-in or spreading of the oil.

5. Herding of the oil with the use of booms or other types of barriers will improve pickup effectiveness because herding increases oil thickness at the disks and eliminates disk starvation. Current, whether natural or caused by towing the disk unit through the oil, will also increase oil thickness at the disks and help to eliminate disk starvation.

6. Tests carried out in waves in both the 10-foot trough and the model towing basin showed that the disk system is very insensitive to waves with regard to oil pickup. In fact, there was a tendency to pick up more oil at a given time in waves which were not choppy enough to cause oil entrainment with the water.

The disks must be large enough in diameter, and their motions relative to the sea surface must be modest enough that the disks are never immersed beyond the lower half of the axle, or that they come out of the fluid surface.

One advantage of the disk system in waves is that it does not disturb the oil surface as would a rotating drum; this was also demonstrated by the model tests.

Disturbing the oil causes entrainment and transfer of oil to greater than pickup depths, thus reducing pickup effectiveness.

SECTION II

RECOMMENDATIONS

It has been shown that a simple multiple disk unit can be designed with a practical sizing and with modest power requirements, to pick up the required 50,000 gallons per hour of oil types ranging from Bunker 'C' to light diesel. This can be done in 5-foot seas combined with 2 knots current and does not require a complicated disk section, expensive material, or high rotational speeds. Water content should be well under the 10% or less requirement; therefore, a separator may not be necessary.

The total recovery system is expected to consist of the disk unit, a herding barrier, support platform and the storage unit. The disk recovery effectiveness is dependent upon the interactions of these units and although the preliminary analyses indicate that these interactions are minimal, further experimental verification, preferably in full scale, is recommended.

In addition, further study of anti-starvation deflector plates between the disks should be performed. Again this evaluation should be conducted in near full scale.

SECTION III

INTRODUCTION

A study to determine the effectiveness of rotating disks for the recovery of oil in the open ocean was conducted for the Department of Interior, Federal Water Quality Administration. This report describes the results of this study. Rotating disks for oil recovery afford the following potential advantages:

1. Removal of oil from the sea surface while collecting a minimum amount of residual water, thus reducing the need for subsequent oil-water separation.

2. Minimum sensitivity to wave forces which reduces stresses in the system.

3. Minimum sensitivity to debris and other foreign objects.

Oil harvesting units presently available for open ocean use are limited by their low recovery capacity, high air/water content and/or rapid loss of efficiency in wind and waves. A successful recovery system must have a high recovery rate even in a relatively severe sea condition, minimum sensitivity to wave forces, and be economical and easily employed.

A recovery system used successfully in limited sea states is the rotating drum. This system utilizes the principle that the oil will readily adhere to the drum surface, from which it is recovered with a wiper. It is capable of recovering the oil with viscosities ranging from light diesel to Bunker 'C' grade oil. The low water content of the recovered oil eliminates any need for an oil-water separator or for discharging the entrained water overboard.

The rotating disk system utilizes this principle of recovery, but because it increases the wetted surface area, it has a potential for greater recovery capacity.

The evaluation program consisted of:

1. Laboratory tests of several disk material candidates.

2. Experimental tests of the disks in still water to establish baseline performance data and to determine scaling effects.

3. Experimental tests of the disks in the tow tank in current and waves.

4. Comparison between theoretical analysis and experimental data and the derivation of non-dimensional scaling coefficients.

5. Preliminary sizing recommendation for a disk unit for the recovery of 50,000 gallons of oil per hour.

The study was made for oil types ranging from light diesel to Bunker 'C' oil.

SECTION IV

EXPERIMENTAL PROGRAM

The experimental program was divided into three parts:

1. Laboratory dipping tests to determine the best material for oil pickup.

2. Tests in a 10-foot long trough to establish the scaling laws with regard to disk diameter, depth of immersion and rotational speed in a range of oil types and slick thicknesses.

3. Tests in a 300-foot towing basin to find the effects of current and disk spacing at various rotational speeds on oil pickup rates for various oil types. Tests were conducted to find the effect of waves combined with current on pickup rate for one oil type. Tests were also made for one oil type to determine the best direction of rotation of the disk relative to the current.

The experimental program was tailored to a theoretical analysis of the mechanics of oil pickup. Based on the results of the Reference 1 studies, it was felt that the effects of wind could be adequately covered by considering wind as an equivalent current; therefore, no wind tests were performed.

OIL RECOVERY MATERIAL EVALUATION

This evaluation was performed to determine suitable materials for recovery of floating oil. The materials were evaluated for use in oil harvester disk tests to be performed under the following sections.

Materials were evaluated against a full range of oil varieties (diesel fuel, Bunker 'C', and crude oil) to determine percentages and quantities of oil and water retained under controlled conditions.

Additional tests were conducted in mixtures of Bunker 'C' and diesel fuel against aluminum to evaluate variations with viscosity.

Eight materials were selected for evaluation: Polypropylene, Polycarbonate, Polyethylene, Teflon, Neoprene, Aluminum, Stainless Steel, and Mild Steel. Samples measured 1" x 2" x 1/16" thick untreated. Total surface area for each sample was determined to be approximately 4.3 square inches.

STATIC TESTS IN A 10- FOOT TROUGH

This evaluation was performed to determine the effect of various parameters on the oil pickup rate of a rotating disk. Most of the tests were performed with a single powered disk of the optimum material which turned out to be aluminum, as determined by the material evaluation tests, cost analysis, machinability, and reliability analysis. The oils used were diesel oil, 40-weight motor oil and Bunker 'C' fuel oil. The parameters which were varied sequencially were disk diameter, disk immersion depth, disk rotational speed, static oil slick thickness, and wiper gap. Brief tests in diesel oil investigated the effect on oil pick-up rate of multiple disks side by side, and also the effect of disk immersion cycling to simulate waves. Disk diameters ranged from 8 to 18 inches, immersion depths from 0.5 inches to 6 inches, rotational speeds up to 0.8 revs/sec, slick thicknesses from film to 2.5 inches, and wiper gap from 0.025 inches to zero with rubber wipers, to pressure with rubber wipers for diesel oil pick-up.

Brief tests were conducted in diesel oil with five 18-inch diameter disks spaced 1.5 inches apart, with eight disk sides wiped with positive pressure rubber wipers. (Note that these tests could only be performed with diesel oil because of the high rate of oil pickup.) Waves 5 inches by 1.6 sec. period were simulated by disk immersion oscillation.

TESTS IN A 300-FOOT TOWING BASIN

The oil recovery test program was conducted at the General Dynamics Convair Marine Test Facility model tow basin from 24 September through 2 October 1970. The equipment used in these tests was the multiple disk oil recovery machine, with 18-inch diameter disks. The test section was 100 feet long by 2 feet wide by 4 feet deep, open at the bottom. The test program was divided into a number of sections; in each section, one or more of the test parameters were varied. Most tests used 40-weight motor oil. The first tests involved running a battery of five disks at 1.5 inch spacing with disks rotating both with and against the current to determine the best operating condition for all subsequent tests.

Tests were then conducted with variations of disk immersion, oil thickness and disk rotational speed up to 2 rps, in current speeds up to 3 knots in smooth water. Further tests were made similar to those above with two other disk spacings. All of these test runs used 40-weight motor oil.

Tests were run in regular waves combined with current in one oil thickness and two disk immersion depths, using 40-weight oil.

The last thirty test runs of the test program were made with Bunker 'C' oil one inch thick, at a disk spacing of 1-1/2 inches. The test fixture could not handle the quantity of oil and the disk drive motor could not maintain a constant speed during a run with the original multiple disk machine; for this reason, the data obtained in the first four runs is suspect. The test setup was then modified, but with only partial success. Tests with Bunker 'C' oil were discontinued. No tests of this type were performed with diesel oil.

SECTION V

DESCRIPTION OF TEST APPARATUS

MATERIAL DIPPING TESTS

1.	Scale, microgram	Mettler, type H6T dig Cap 160g
2.	Desiccator	Pyrex: Sulphuric Acid desiccant
3.	Beaker	1000 m 1
		250 m 1
4.	Test Specimens 1" x 2" x 1/16"	Composition perd escription under experimental program

STATIC TESTS IN A 10 FOOT THROUGH

The test apparatus is shownph otographically in Figures 1, 2 and 3. A water tight mirror box was inserted in the galvanized steel through so that a view could be obtained under the oil surface. The aluminum disk was driven via bicycle gears and chains by a 1/12 H.P. A.C. motor with variable speed control. A second 1/12 H.P. variable speed motor powered the disk immersion cycling, and was also used to set disk immersion statically. The speed range of the disk was about 0.3 to 0.8 r.p.s. Oil wipers were either slots in an aluminum sheet, with small clearance to the disk; or rubber wipers with close contact, when using Diesel Oil. The wiped oil was drained into a sliding container of 1 gallon capacity, which could be removed for draining into a transparent plastic bucket to permit checking water content of the sample. A large number of these plastic buckets were kept on hand as sometimes the samples had to stand for several hours for complete oil-water separation. Pint graduation marks on the outside of the buckets were used to check volumes.

Ancillary appartus consisted of accurate weigh scales and a stop watch.

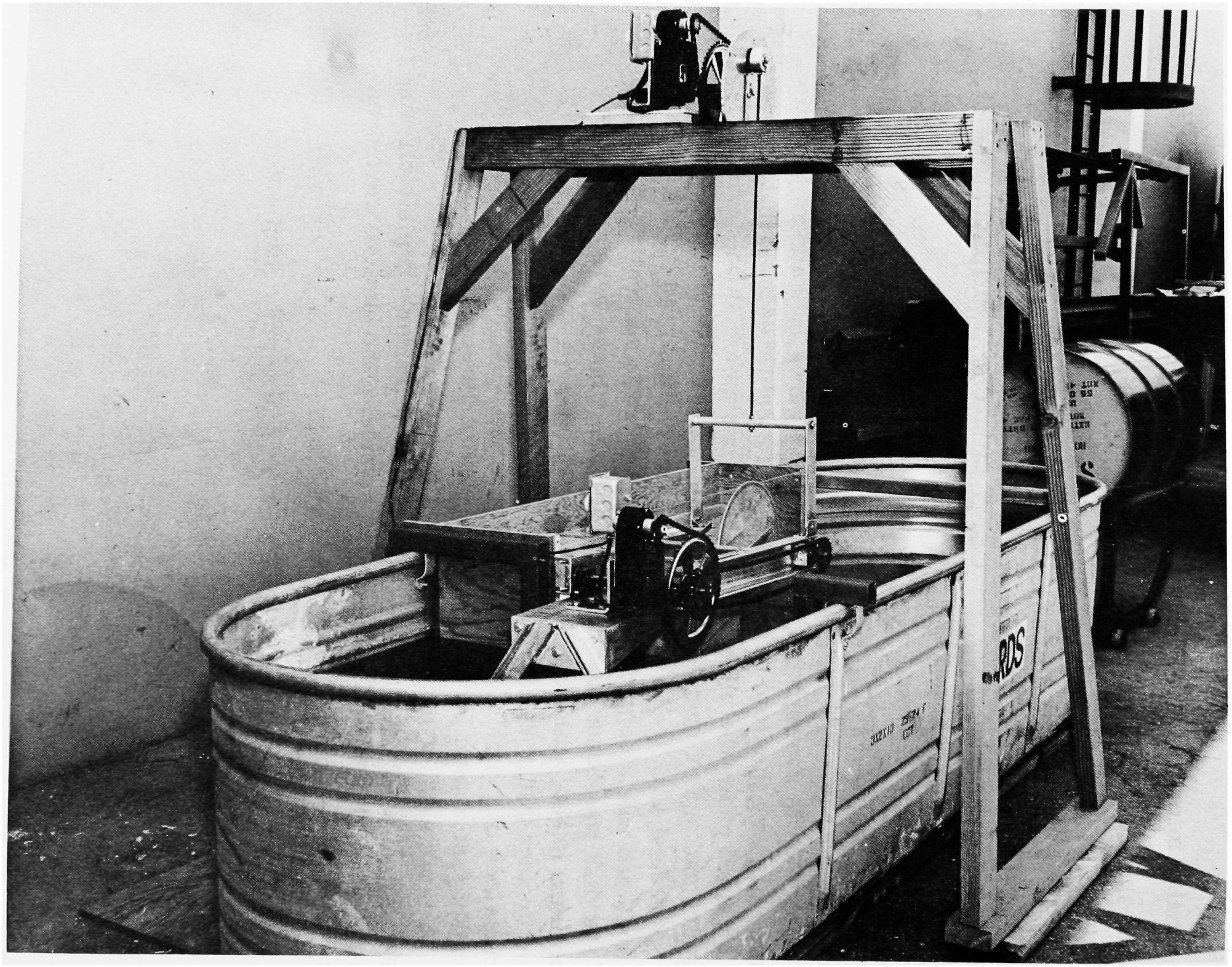


Figure 1. Oil Recovery Test Set-Up in 10 Foot Trough

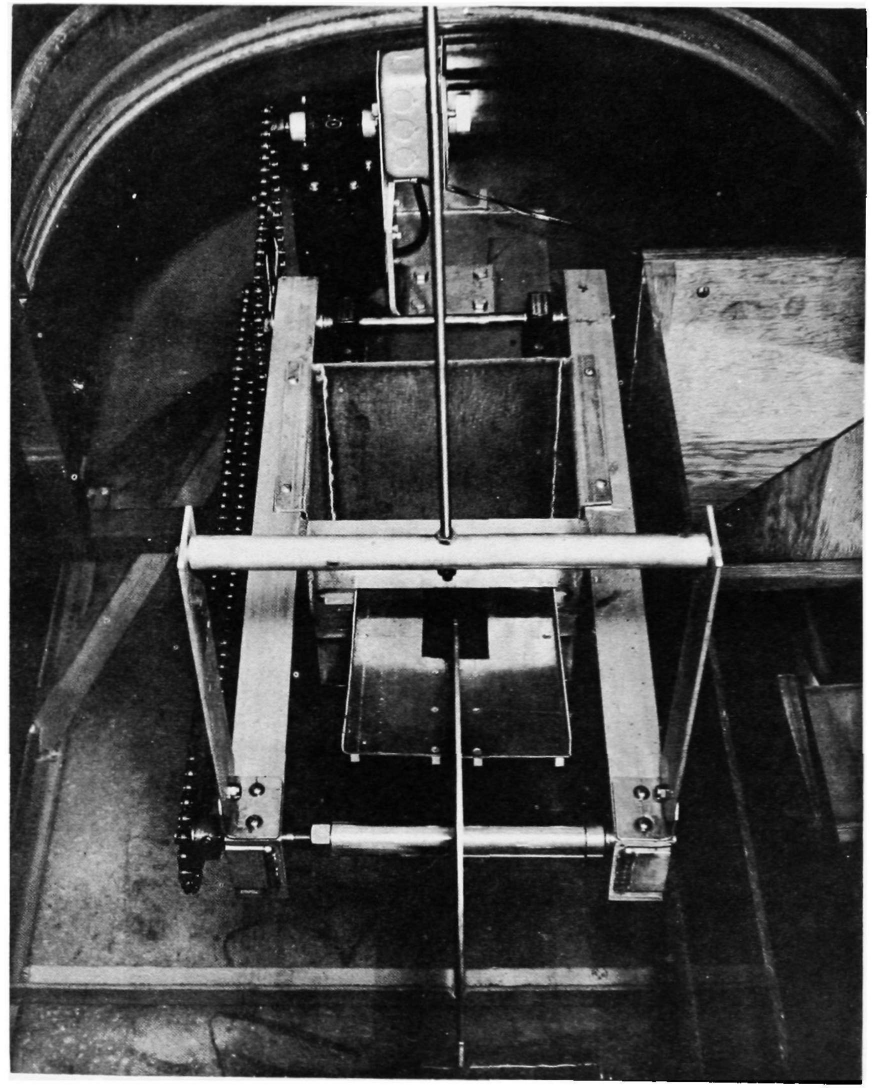


Figure 2. Oil Recovery Test Set-Up in 10 Foot Trough

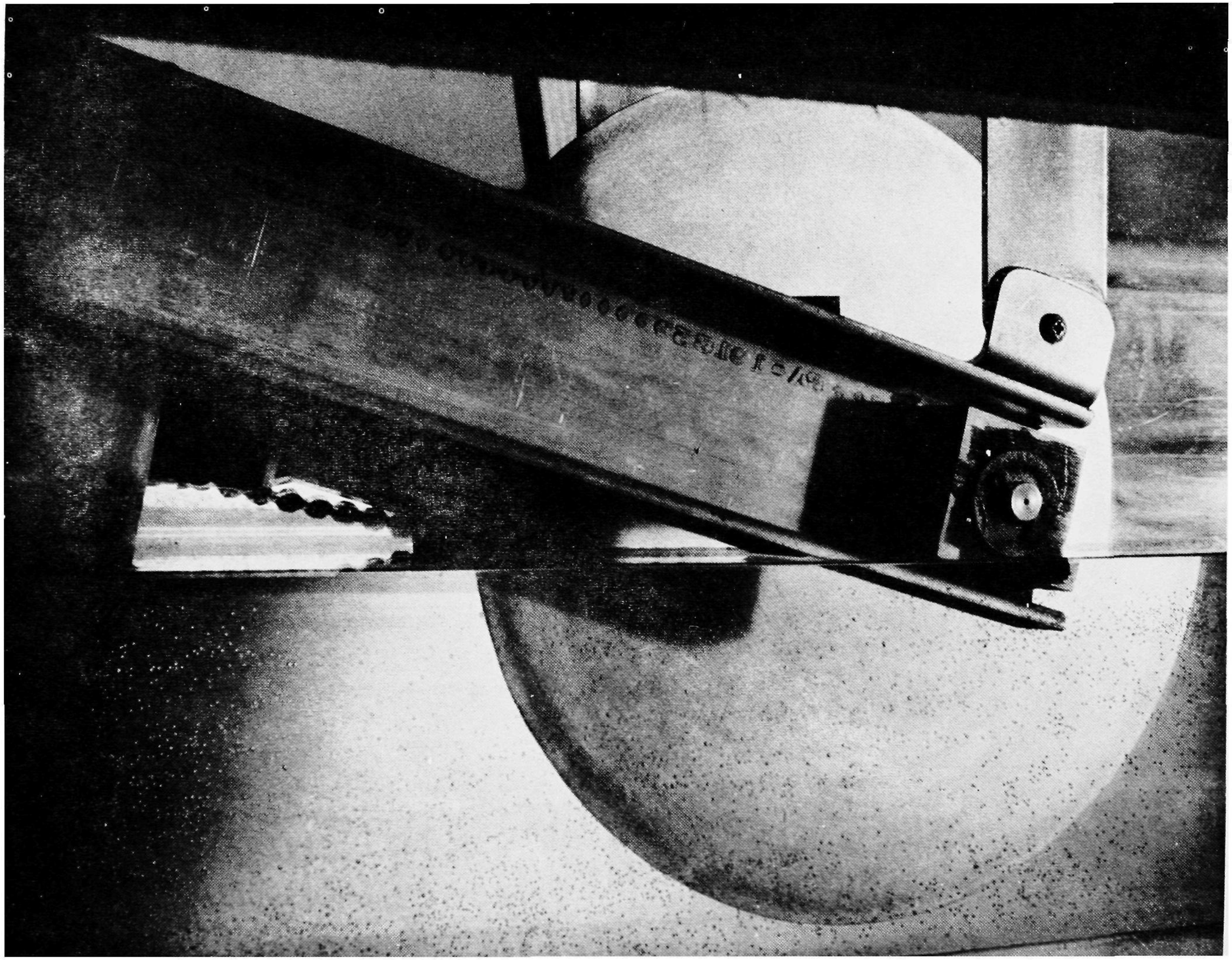


Figure 3. Single Disk Assembly in 10 Foot Trough

TESTS IN A 300 FOOT TOWING BASIN

The test basin is operated by General Dynamics, Convair, in San Diego, and is described in Ref. 5.

It was completely lined with polyeurythene plastic, and a separate wooden trough without a bottom was constructed inside of it. The test trough was 100 feet long, by 2 feet wide by 4 feet deep, open at the bottom. A 50 foot length of one side was made of plexiglass to permit flow visualization and photography. Figures 4a and 4b show the test set-up. The multiple disk oil recovery machine is shown in figures 5a and 5b.

The disk machine was mounted on a plywood base-board, which in turn was attached to the under frame of the tow-basin carriage. The carriage carried 110 volt power for operating the 1/4 H.P. variable speed disk drive motor, and the 1/12 H.P. disk immersion cycling motor. It also carried power for cameras and lights. A mirror box, also attached to the tow basin carriage, enabled the test conductors to see the flow conditions of the under-surface of the oil, and also to photograph flow phenomena. The 8 foot long box canoe carried a large mirror set at 45 degrees to the water surface. Observation was through an eight inch column of water between the plexiglass canoe wall and the plexiglass through wall. This presented no proglems as the water in this region was clear of oil. The oil behavior characteristics were recorded using a still camera taking 2-1/4 x 3-1/4 inch black and white pictures at a maximum frequency of about one every two seconds. Each print showed camera number and run number, a clock with a seconds sweep and a counter for picture-data indentification.

It has originally been intended to collect the oil in a shallow tray at the disks, and then pump it via a "puddle sucker" up into 5 gallon plastic cans on a second tow basin carriage. However, preliminary pumping tests showed that the collected oil is emulsified into a foam, and it would be very difficult to separate out the water from the collected oil. Therefore, it was decided to collect the oil in shallow pans at the disk wipers. After the first few test runs, where all 5 disks were wiped and collected, giving large collection

Figure 4a

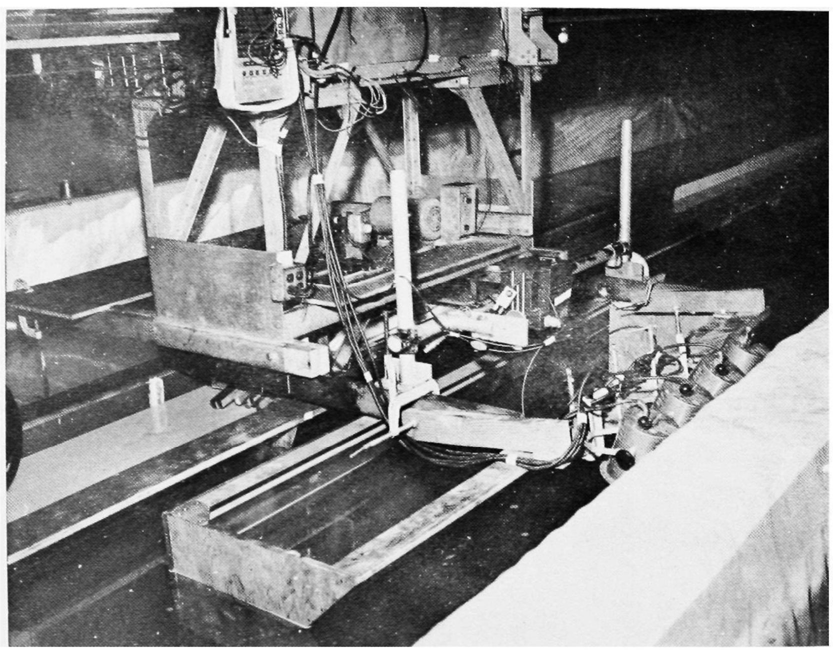


Figure 4b

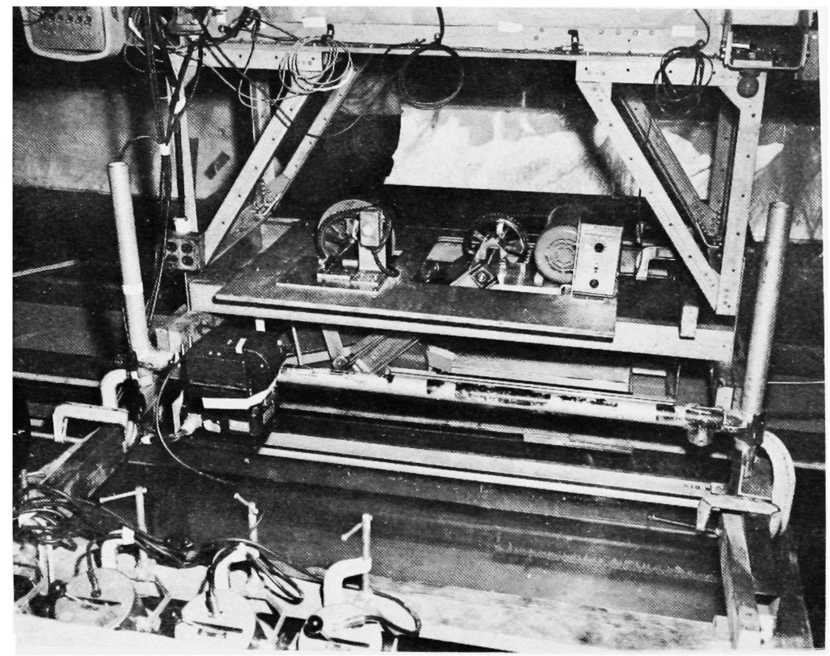


Figure 4. Test Set-Up in 300 Foot Two Basin

Figure 5a

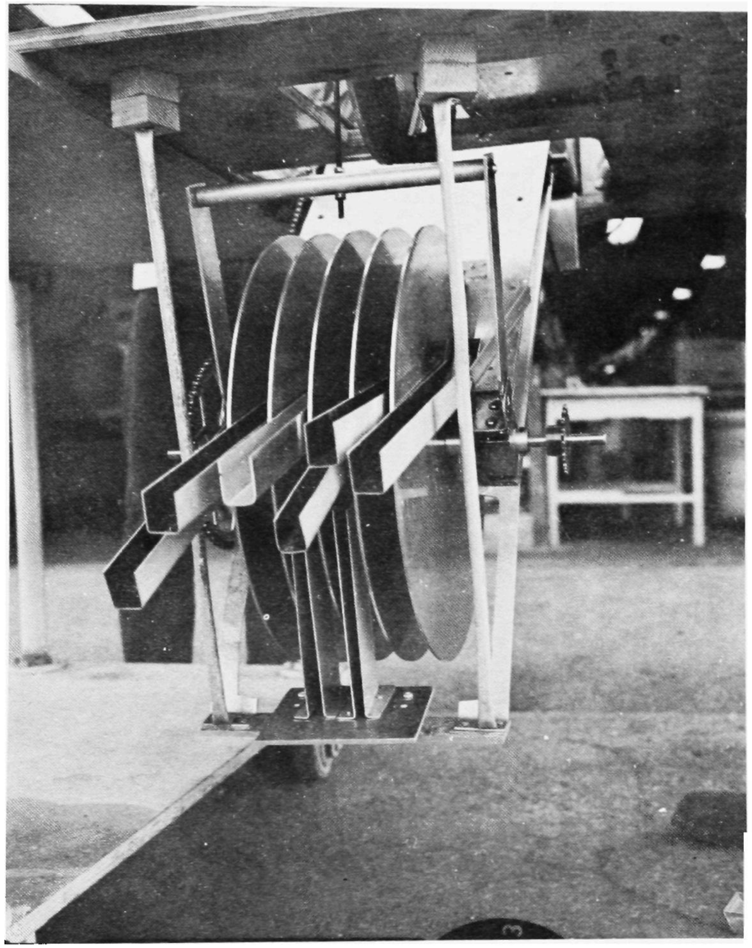


Figure 5b

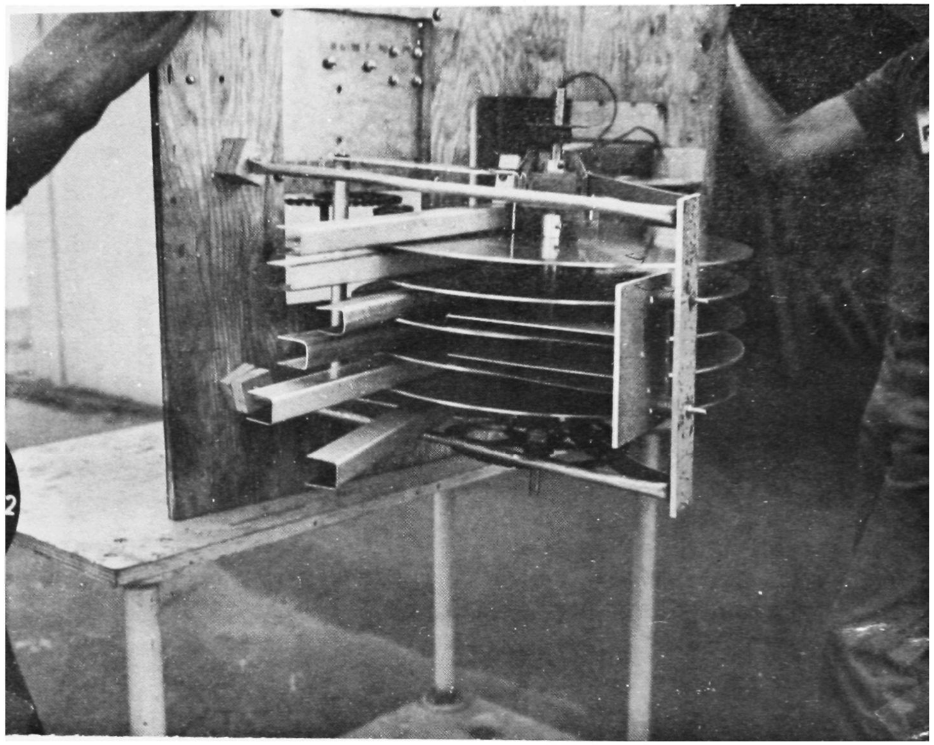


Figure 5. Multi-Disk Tow Tank Test Model

volume, it was decided to wipe all 5 disks, but collect from only the center one. Depending on the volume collected on one run, collection vessels used were as follows:

1. Large shallow pan - capacity when dry 1.244 gallons, and capacity when primed with 40 wt. oil, 1.169 gallons.
2. Small shallow pan - capacity when dry 0.645 gallons and capacity when primed with 40 wt. oil, 0.604 gallons.
3. One-quart size glass fruit jars.

Ancillary apparatus consisted of accurate weight scales and a stop watch.

SECTION VI

TEST PROCEDURES

MATERIAL DIPPING TESTS

The testing was divided into two phases:

> Phase I: was conducted with cleaned water wetted samples immersed in the water and drawn up through the test oil floating on the water surface. Samples were withdrawn at a constant eight second rate per sample.
>
> Phase II: was conducted with a thin film of test oil applied to the entire sample surface. Samples were lowered through the test oil slick into the water and then raised up through the slick again each at the same eight second rate per sample.

Each material was evaluated in each of the oil types with the exception of the Bunker 'C'/Diesel mixtures, of which only the aluminum was evaluated. Water used in all tests was tap water.

Each sample was cleaned prior to each test, placed in an aluminum cup, and a dry, or film coated, weight measurement was made and recorded. Samples were then immersed in the oil and an oil plus water measurement made and recorded. Samples were then placed in a desiccator overnight to draw out any retained water. Weight measurements were made after the drying cycle which showed the total oil retained by each sample.

Using the above measurements it was possible to calculate total oil and water retained by each sample; percentage values were also calculated. This percentage of oil pickup is equal to the volume of oil picked up divided by the total volume of oil and water picked up expressed as a percent.

Oil used in the evaluation was obtained from Terminal Annex, San Pedro; no special handling was involved, the Bunker 'C' being a partially refined crude oil.

STATIC TESTS IN A 10 FOOT THROUGH

The procedure was to pour oil into the trough to a specified static thickness which was measured in the mirror box. The aluminum disk was then set to the required immersion depth using the depth cycling motor. For the 18 inch diameter disk the wipeable disk settings were up to 6 inches immersion; for the 12 inch diameter disk up to 4.5 inches, and for the 8 inch diameter disk, only up to 1.5 inches. Disk revolution speed was set and counted orally using a piece of red tape on the shaft. The 1 gallon capacity collection pan could be slid on tracks under the wiper tray or drawn back on command. Time elapsed during a test run was measured by a stop-watch. The collected oil was poured into a transparent plastic bucket and weighed. After standing for some hours, the total volume and the volume of water was read on the graduation marks on the sides of the buckets. Hence percentage water content was calculated. The only oil for which this could not be done was the Bunker 'C' which coated the plastic buckets so badly, that the "tarry" oil had to be poured off until a water surface appeared. The water content was then estimated.

Optimum wiper gaps turned out to be 0.025 in. with Bunker 'C' oil, light contact with rubber wipers for 40 wt. motor oil and pressure contact with rubber wipers for diesel oil.

The 40 wt. motor oil emulsified rather easily, and the water that went into the emulsion did not settle out with standing. Excess water did settle out. Diesel oil emulsified after several days use with a thin slick, but although the quantities picked up were small, the equipment handled it rather easily. The Bunker 'C' oil slowly turned to tar and jammed up the equipment after a few days, making further testing impossible without a complete clean-up.

The drive motor for disk rotation was underpowered, but it was possible to obtain four distinct speeds up to 0.8 r.p.s. with a single disk.

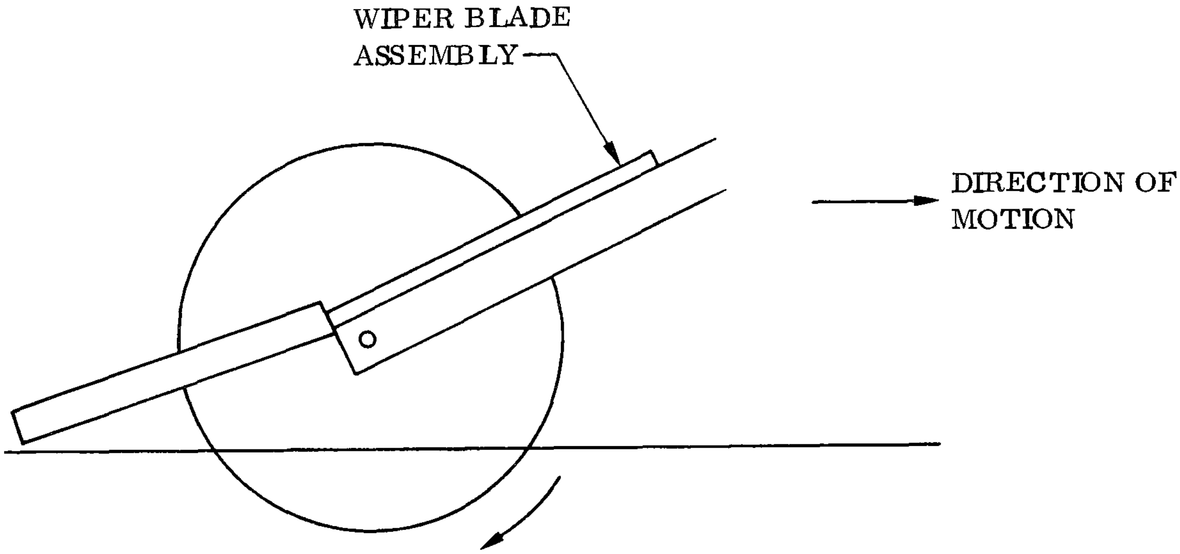
Multiple disk test and wave simulation tests were only performed with diesel oil. The former tests were performed with diesel oil because the equipment could not have handled the high pick-up rates with the other oils. The wave simulation tests were performed with diesel oil because this oil coated the disk very precisely, without local build-ups of oil, even though the actual oil coatings were very thin. Diesel oil could also be wiped very cleanly, and specimen weighing was accurate because the plastic buckets could be emptied completely between use. A total of 246 test runs were made in August and September 1970.

TESTS IN A 300 FOOT TOWING BASIN

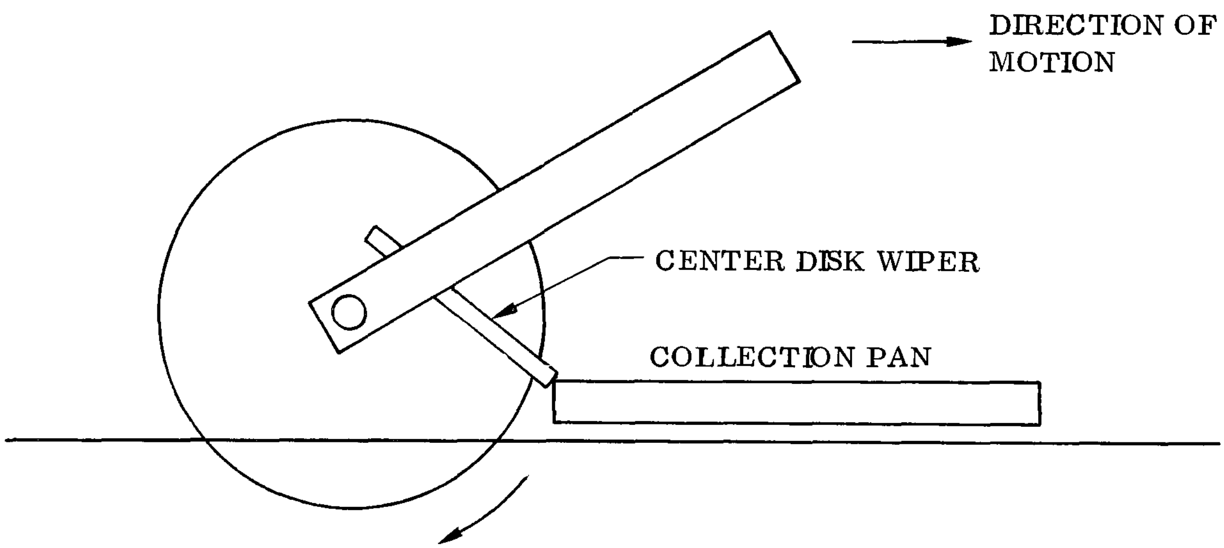
The tests were started on the 5 disk system with all sides wiped and collected, but the quantity of oil collected was so great that after the initial runs to find the best direction of disk rotation relative to the current, it was decided to continue wiping all dsik sides but collect from only the center disks. The oil from the other disks was carried in individual troughs well aft of the pick-up area. (See figure 5).

Because the pump could not be used to carry the collected oil away from the disks due to excessive frothing, good team work was necessary to collect the oil accurately. The first choice was a large flat pan of volume 1.17 gallons which had to be completely filled in one run. If there was not enough oil to completely fill the large pan in one test run, the second choice was a small flat pan of volume 0.60 gallons which had to be completely filled, and if there was not enough oil for this then the oil was collected in a 1 quart glass fruit jar, which was not necessarily completely filled. A glass jar sample was used to visually check the water content in the pick-up. If it was apparent that there was negligible water content, then the pan was filled and no jar sample was collected for water content. (Note: a jar sample purely for water content was taken from disks other than the center disk).

For most of the test runs, the disks rolled with the current, and the pan samples were collected ahead of the disks, while the water content jar samples were collected aft of the disks. Figure 6 shows the oil collection system.



2 OUTSIDE DISKS ON EACH SIDE
OIL SPILLED BACK INTO TROUGH WELL
AFT OF DISKS.



CENTER DISK COLLECTED IN PAN

Figure 6. Multi-Disk Test Configuration

The disk wiper system developed during the tests consisted of heavy tape wipers attached to an aluminum frame work. The wiper blade assembly is shown in Figure 7. Heavy tape was placed on slots 1, 2, 4, and 5 and slotted with a knife. Slot 3 in the aluminum was relatively wide and open. Blade 3 was separately wiped and collected.

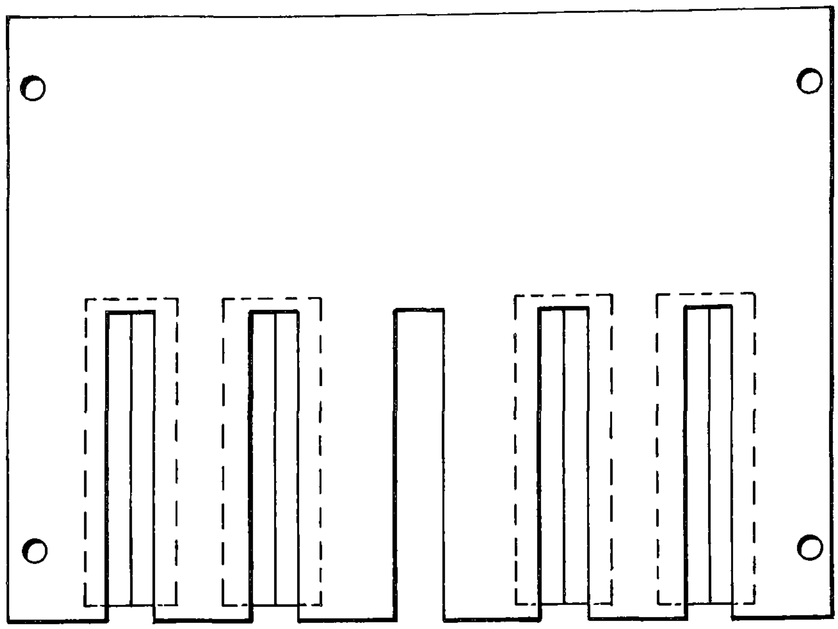
The procedure on any given test run was as follows:

1. Set disk R.P.S. on controller.
2. Tell carriage operator to go at set speed.
3. When speed was reached, he sounded horn.
4. At that time, pushed collection tray under. Started stop watch and revolutions count.
5. Pan would fill up as run continued.
6. At time pan started to overflow, engineer would say MARK. Everyone stopped count. Recorded number of revolutions and time on stop watch.
7. Machine oil collection was stopped.
8. Carriage slowed and stopped.
9. Lifted back end of collection pan as high as possible.

Under surface black and white photographs were taken on most runs by a photographer who was present throughout the testing.

The test program was divided into a number of sections. In each section, one or more of the test parameters was varied. Oil samples were collected each day for analysis to obtain the physical properties of the oil.

The testing occupied 7-1/2 days of tank time at the end of September 1970, during which time 216 test runs were made.



WIPER BLADE ASSEMBLY

HEAVY TAPE PLACED ON 1, 2, 4 AND 5 AND SLOTTED DOWN CENTER ON EACH WITH A KNIFE.

SLOT 3 RELATIVELY WIDE AND OPEN.
BLADE 3 SEPARATELY WIPED AND COLLECTED

Figure 7. Wiper Blade Assembly

SECTION VII

TEST RESULTS

All of the results for the oil dipping test program are listed in Appendix I. Other test data are not listed. Most of the graphs plotted are for tests in zero current where the test conditions could be more rigidly controlled than was possible in the Towing Tank.

The three test programs are separately discussed.

OIL RECOVERY MATERIAL EVALUATION

Tests have shown increasingly larger amounts of oil retained as the viscosity of the test oil increased, and the drainage from the raised samples decreased. The oil retained per square inch of material varied from 1 to 2 milligrams of diesel fuel to 300 milligrams for the Phase I materials. Phase II materials retained from 10 milligrams to 800 milligrams showing an increase in retention for the oil-wetted surface samples over the water-wetted samples.

The higher viscosity oils, such as Bunker 'C' or crude, showed less variation in amounts of oil retained for the various materials (oil or water-wetted). The heavier oils displaced water when sampled, retaining consistently less than 5 percent water. Lower viscosity oils such as diesel fuel, showed larger variations with material in the amounts retained. Water retained was also considerably more for some, as high as 50 percent. Oil-wetted samples were more consistent in the amounts of oil and water retained, polyethylene showing as the best performer.

No attempt was made to determine optimum pickup rates since only the materials were being evaluated. For the oil-wetted samples, two passes were made through the oil slick, only one pass was made for the water-wetted samples.

Aluminum was evaluated in various mixtures of Bunker 'C' and diesel fuel for its ability to retain oil. Mixtures ranged from 90/10 to 25/75 percent, Bunker 'C'/diesel. Results showed that the higher concentrations of Bunker 'C' retained as much as 600 milligrams compared to less than 100 milligrams for the lower concentrations. See Figures 8 and 9.

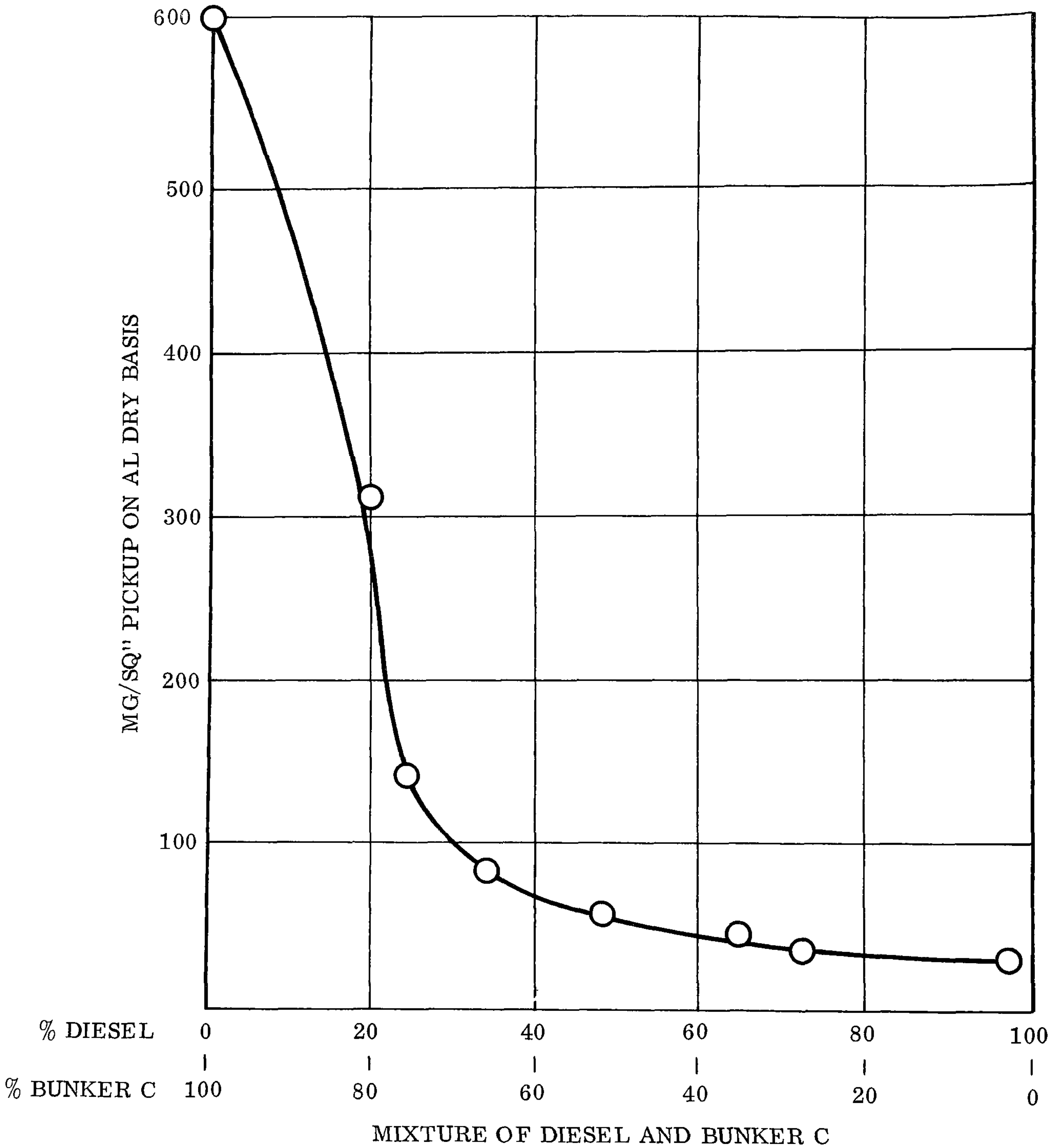


Figure 8. Dipping Tests - Oil Pickup on Aluminum

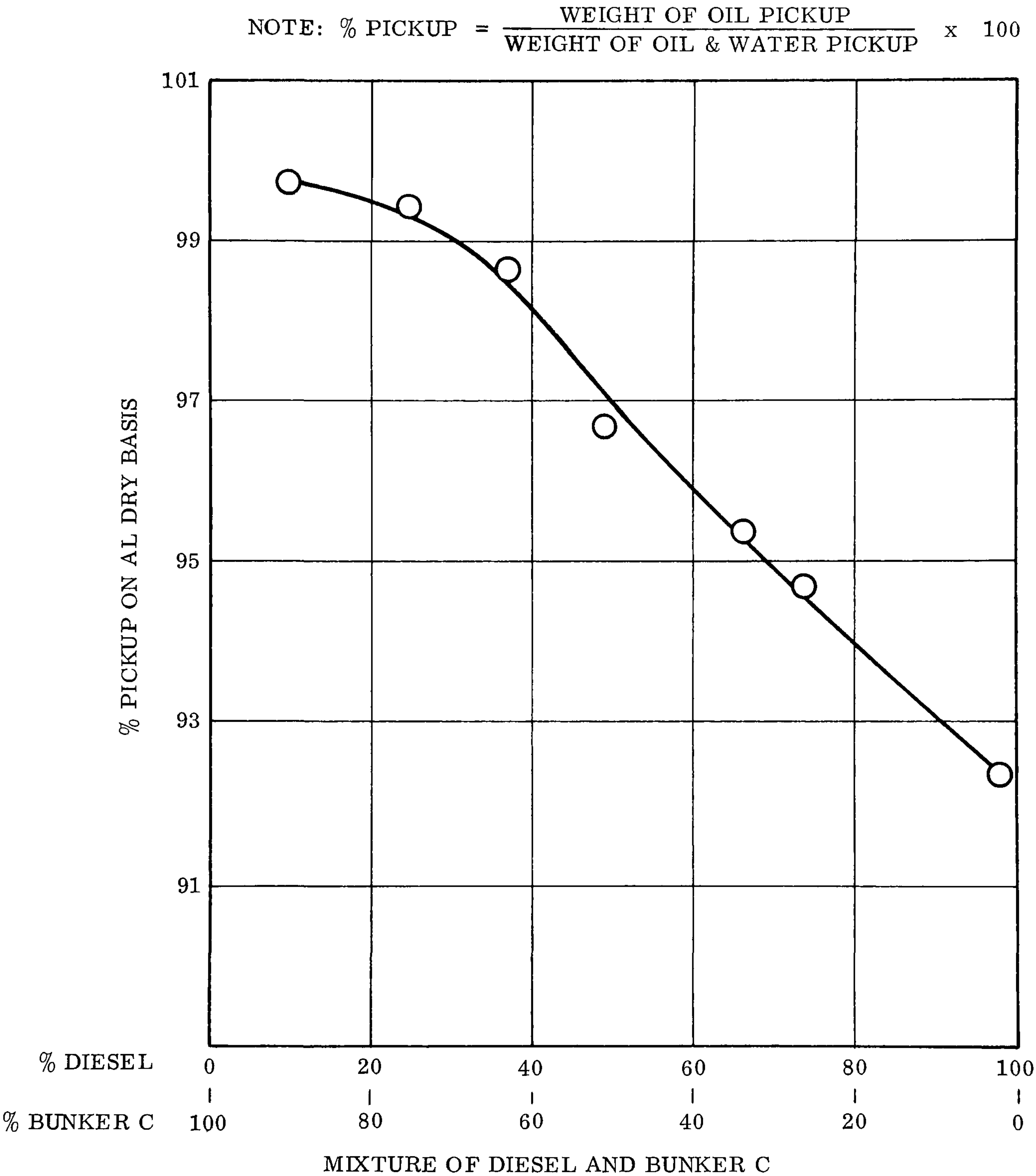


Figure 9. Dipping Tests - Oil Percentage Pickup on Aluminum

In general, Aluminum was determined to be the best overall material. Other materials often proved better in the dipping tests although usually by only the slightest of percentages. However, from a cost standpoint, weight standpoint (ease of handling), machinability and reliability standpoint, aluminum was the most advantageous material.

Any of the non-metallic materials would have to be bonded to a metal in a sandwich fashion for adequate strength. The reliability and survivability of such a composite structure was in grave doubt and the cost was excessive. Of the metallic materials, stainless steel was eliminated due to cost and poor access of materials and mild steel was eliminated due to weight although it was a very close competitor to aluminum and could be a direct substitute.

Figures 8 and 9 show pick-up on a dry basis, and percentage pickup (i.e., % of oil divided by total oil and water pickup), respectively, for various Bunker 'C' / Diesel mixtures.

STATIC TESTS IN A 10-FOOT TROUGH

A total of 246 test runs were carried out for these zero current tests. Ninety-seven runs were made in 40-weight motor oil, 78 runs were made in diesel oil, and 71 runs were made in Bunker 'C' oil. The specific gravity of diesel oil at 77°F was 0.84, of 40-weight motor oil was 0.90, and of Bunker 'C' was 0.98. Further oil data is listed in Appendix II.

The test program was divided into a number of sections.

1. <u>Oil Type 40-Weight Motor Oil</u>

   In this series of tests with a single aluminum disk, various disk diameters were tested at various disk immersions, in various oil slick thicknesses from thin film up to 2.5 inches. About one-half of the tests were made with a wiper gap of 0.025 inches in order to leave a permanent film of oil on the disk, and the remainder of the test runs were made with rubber wipers having light disk contact. It was found that rather more oil was picked up by the rubber wipers, other conditions being equal.

   After the first few test runs, the 40-weight oil emulsified with the water to change from a clear golden brown color to milky light gold.

After this there seemed to be no further change with continued testing. Because of this, the first few runs were repeated in the emulsified oil; Figure 10 shows that at an immersion depth of 1.5 inches with a 12 inch disk in 1 inch thickness of oil the amount of pick-up was unchanged, but that at 4.5 inches immersion about 20% greater pick-up was obtained with emulsified oil. All other graphs are for emulsified oil only and are consistent with one another.

All pertinent data has been put on the graph sheets, Figures 10 to 17 inclusive, and so the firures stand on their own; however some explanation is required. Figure 11 shows the effect of changing from 0.025 in. wiper gap to rubber wipers for a 12 inch disk in 1.0 inch thickness of oil for various disk immersions. Figure 12 shows the effect of disk immersion depth for an 18-inch diameter disk with rubber wipers. At a disk speed of 0.6 revolutions per second, about three times as much oil was picked up at an immersion depth of six inches as compared with an immersion depth of 2.5 inches.

There is some evidence that the graph of pickup quantity versus disk revolutions per second is not linear. This is probably due to starving the disk of oil at the higher revolutions. Further discussion of starvation is presended in paragraph entitled

Figure 13 shows the effect of disk diameter on oil pickup for a range of depths for a 1.0 inch slick thickness and 0.025 inch wiper gap. Figures 14, 15, and 16 indicate the effect of oil slick thickness for an 18-inch disk at various depths of immersion. At a 2-inch immersion depth and a slick thickness of only 3/64 inches, the effect of starving is very ovbious as pickup decreases with increasing disk revolutions. Figure 17 is a cross-plot showing effect of oil slick thickness at a constant disk speed of 0.6 rps. As would be expected, when the slick thickness reaches the immersion depth, there is no further increase in oil pickup with further increase in the slick thickness.

2. <u>Oil Type Shell Dieseline Diesel Oil</u>

In this series of tests with a single aluminum disk, there were similar variations of test parameters as were made with the 40-weight oil, with the exception that all tests were made with the

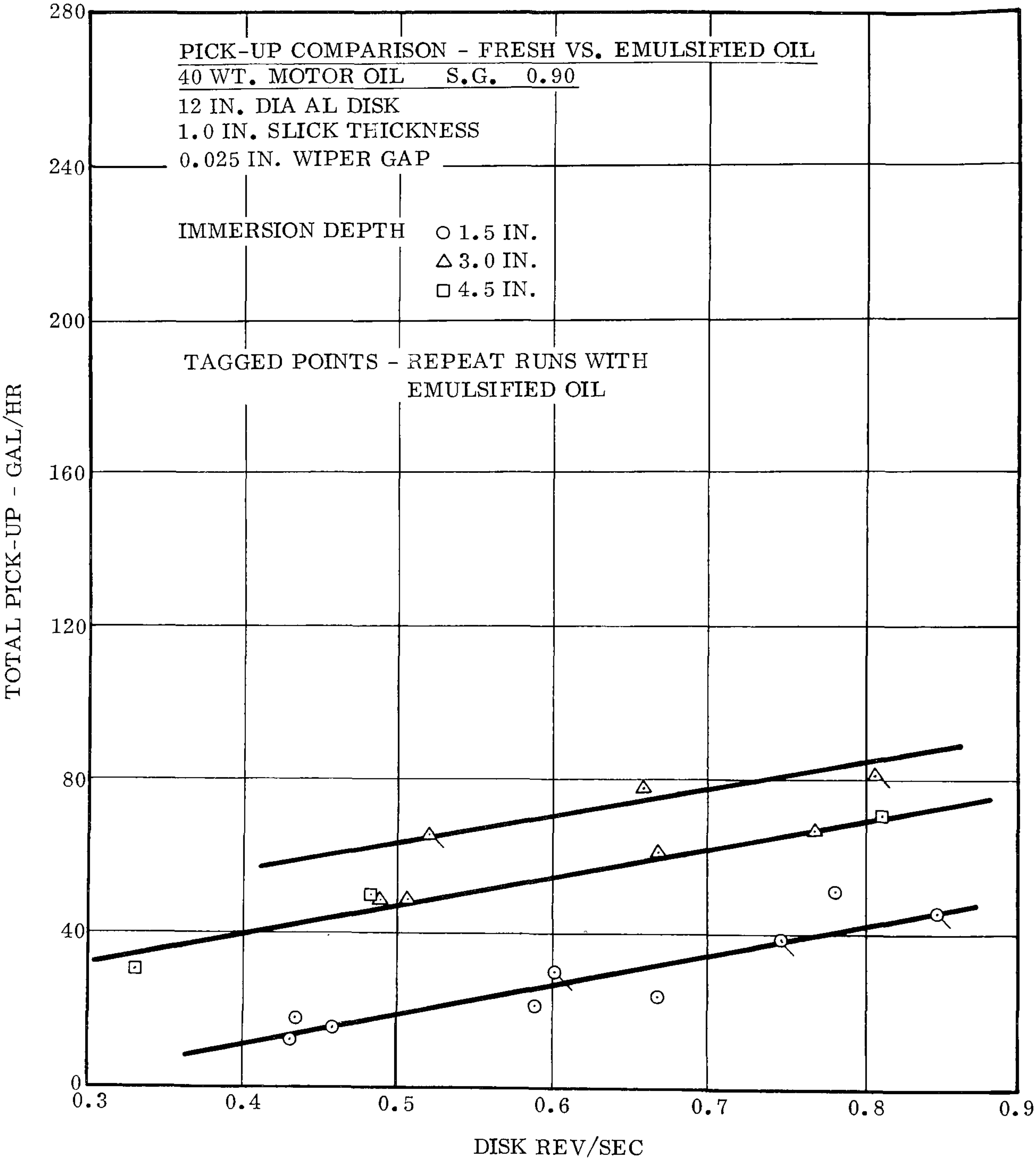


Figure 10. Zero Current Oil Recovery Tests

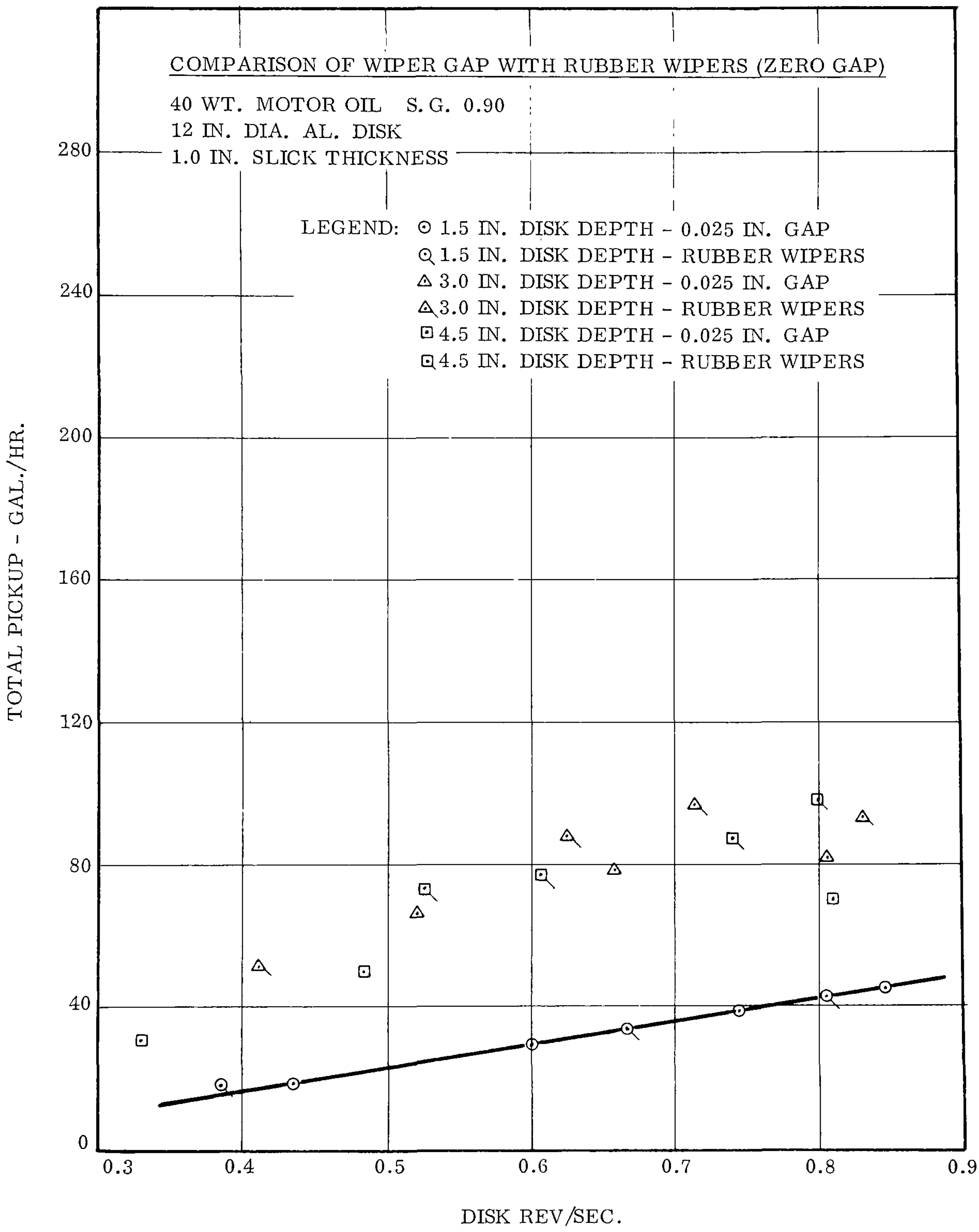


Figure 11. Zero Current Oil Recovery Tests

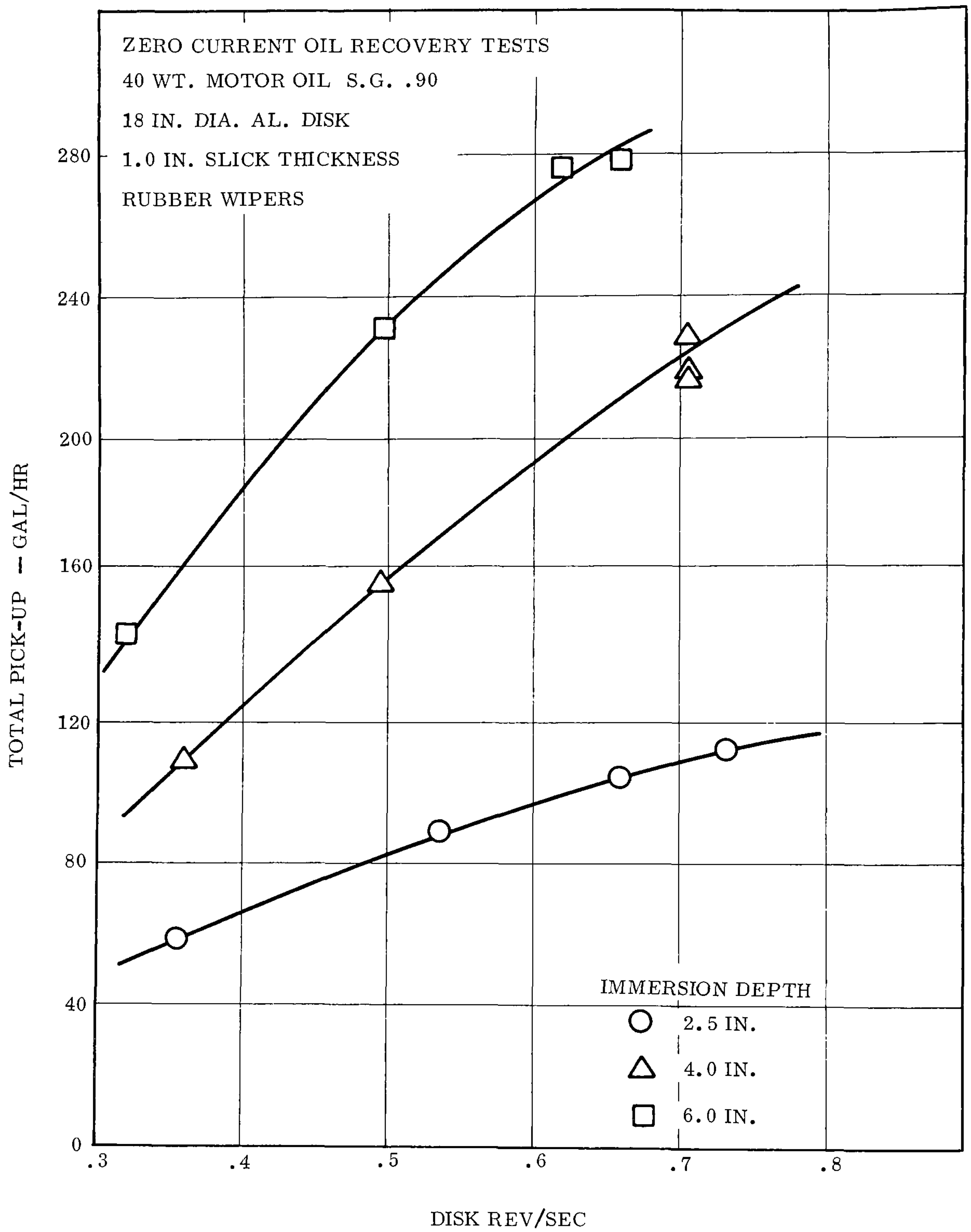


Figure 12. Zero Current Oil Recovery Tests

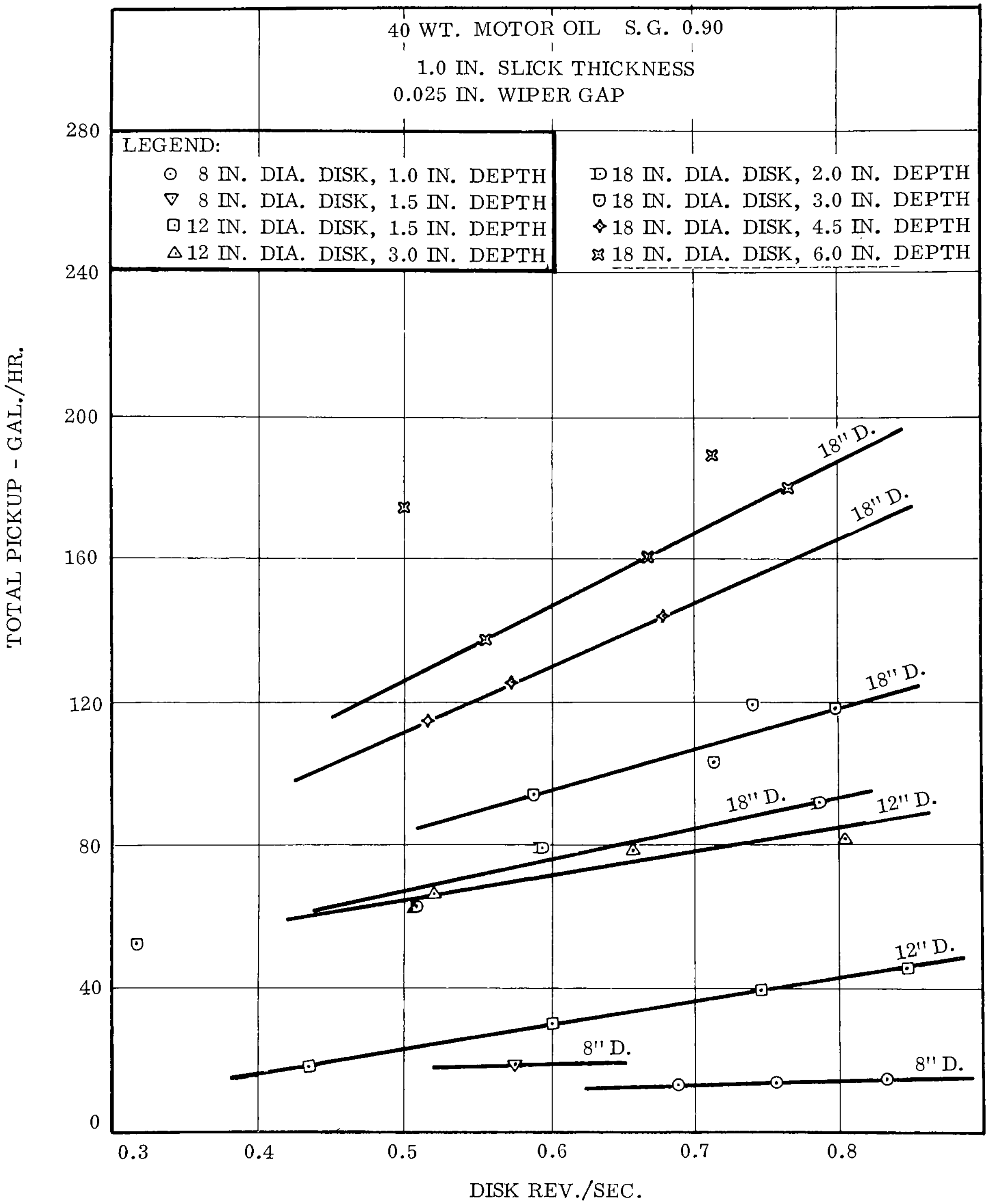


Figure 13. Zero Current Oil Recovery Tests - Effect of Disk Diameter and Depth on Oil Pickup

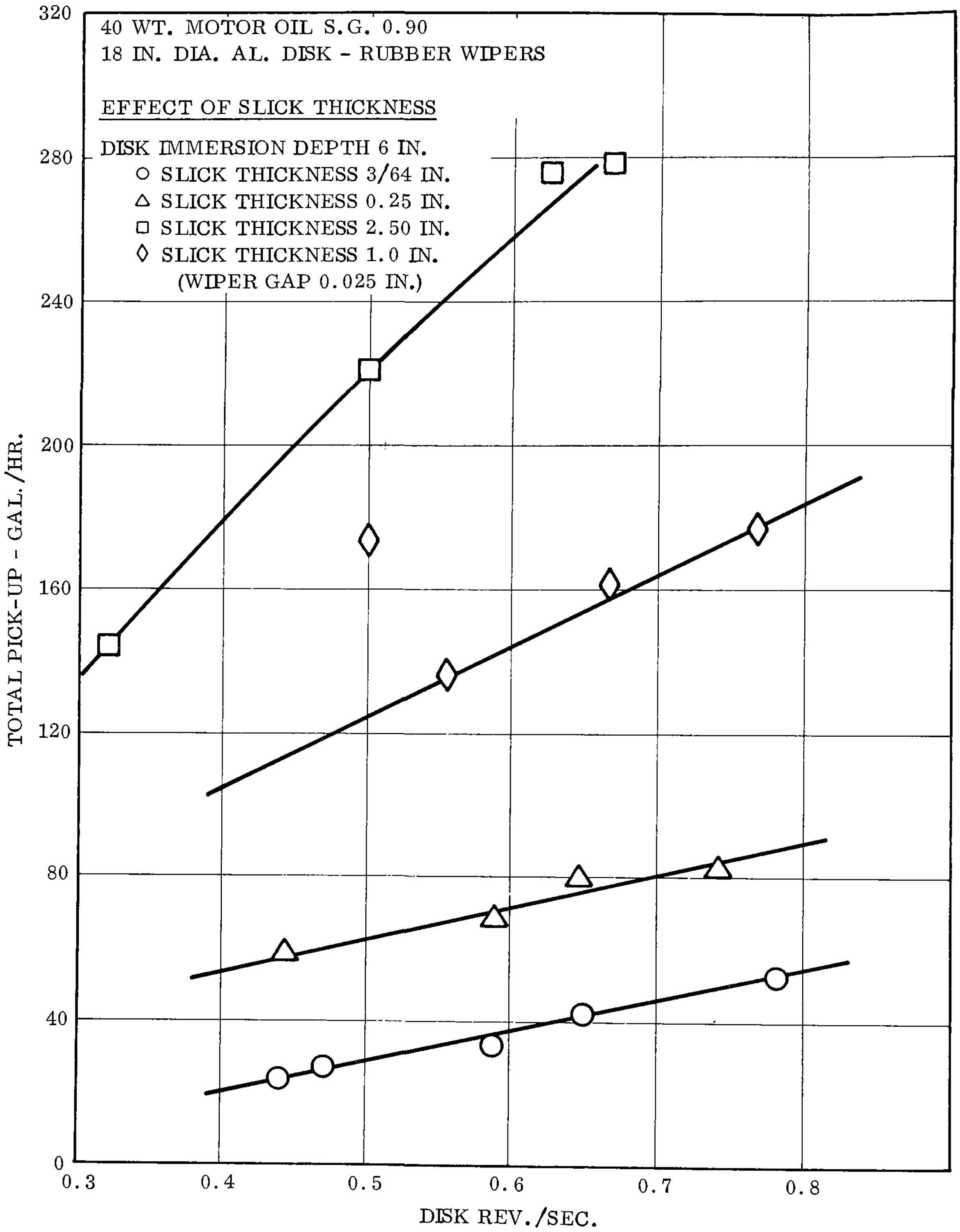


Figure 14. Zero Current Oil Recovery Tests

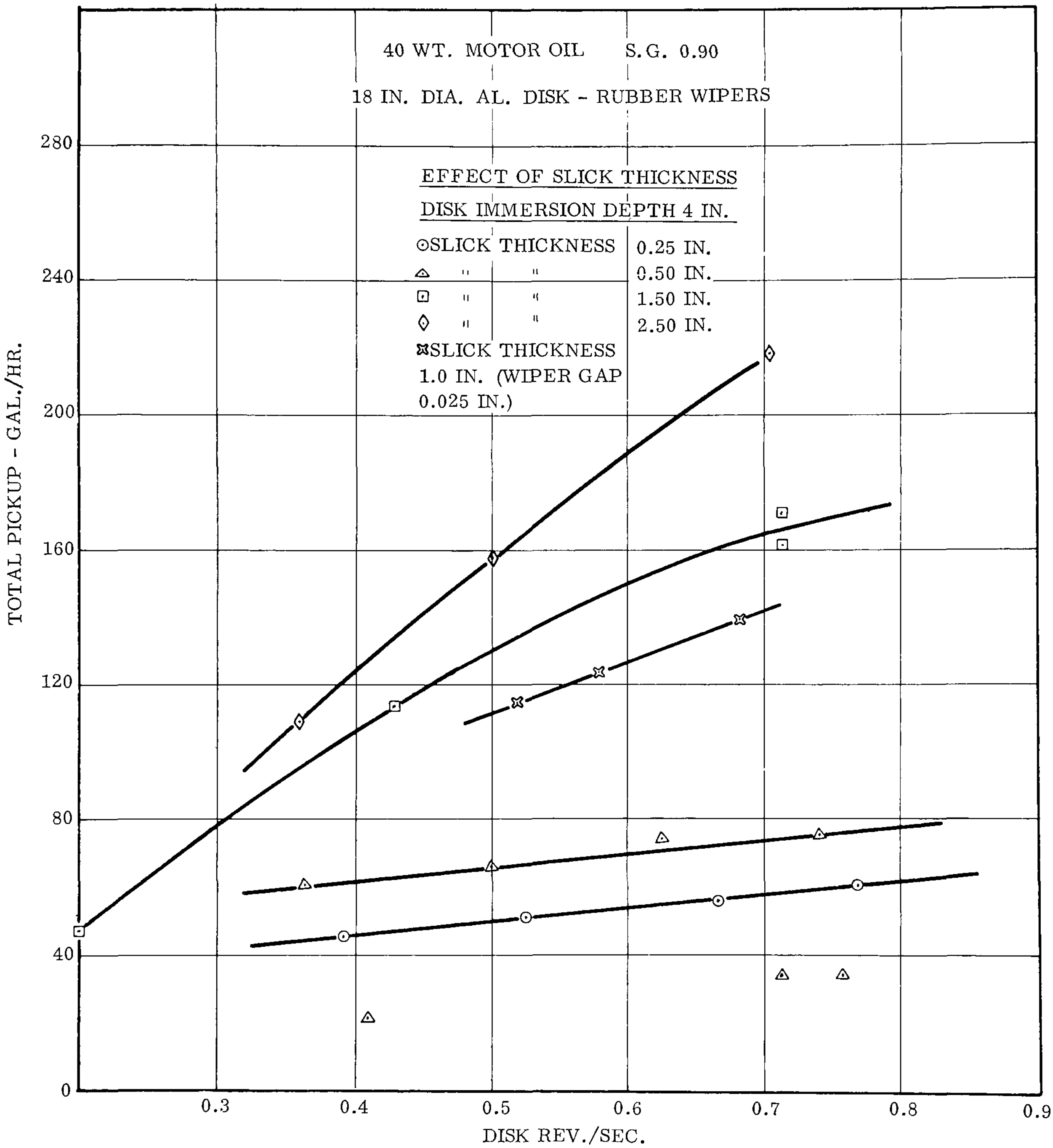


Figure 15. Zero Current Oil Recovery Tests

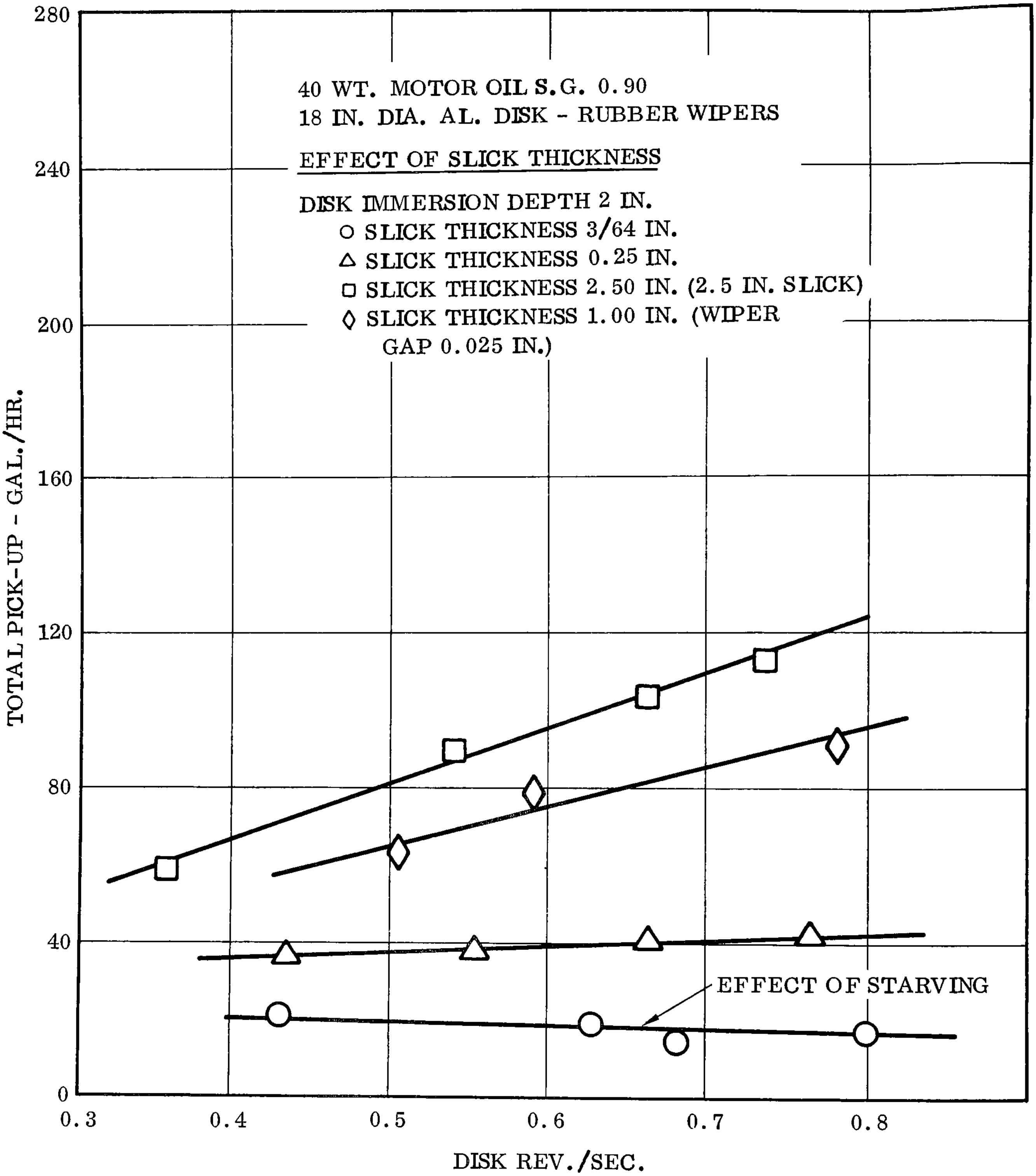


Figure 16. Zero Current Oil Recovery Tests

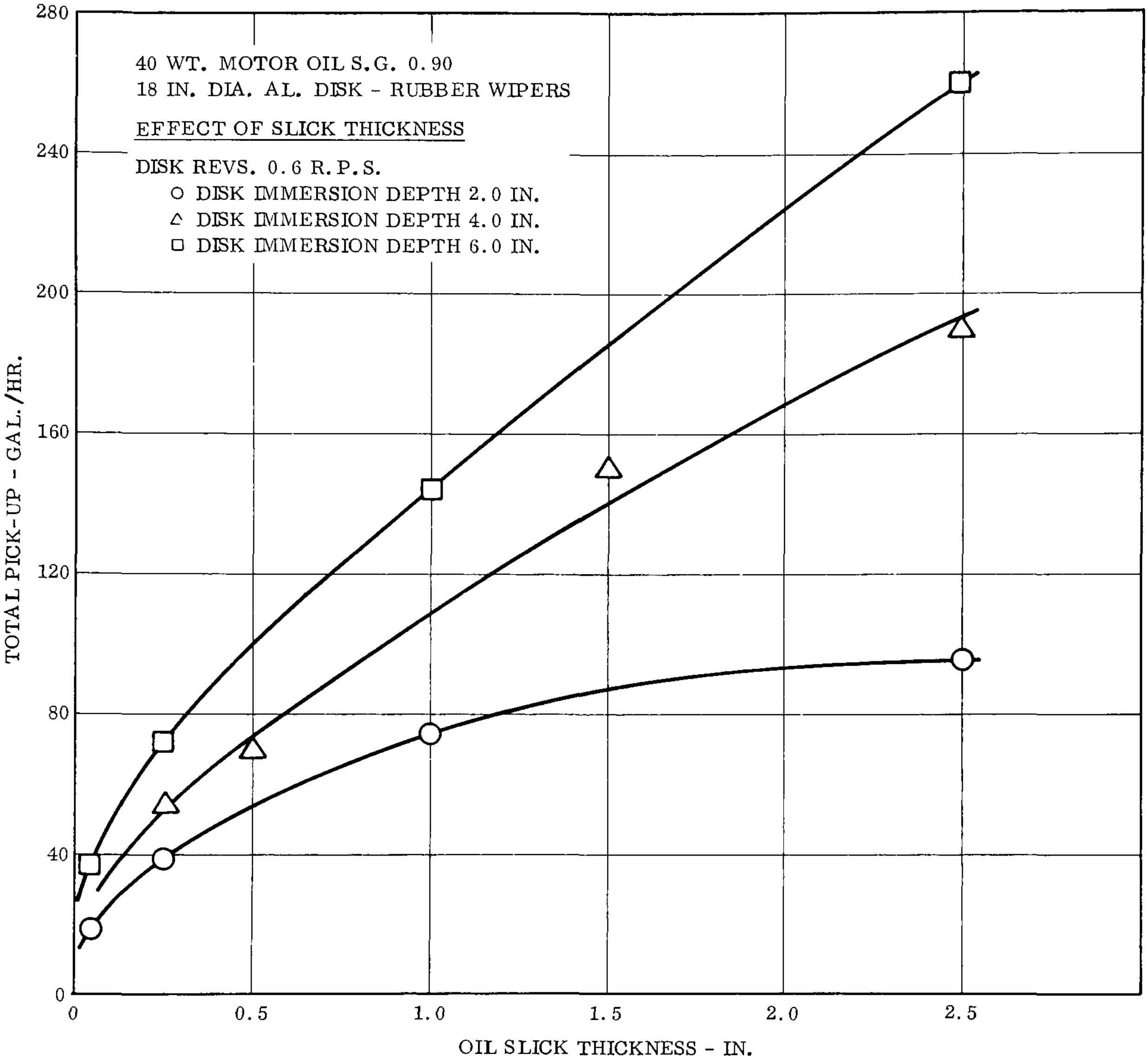


Figure 17. Zero Current Oil Recovery Tests

18-inch diameter disk because oil quantity pickup was low. It soon became evident that there was big variation in oil pickup depending on the wiper pressure of the rubber wipers. Figure 18 shows that more than twice as much oil was picked up with heavy wiper pressure as compared with light wiper contact. Consequently, all further testing with diesel oil was made with heavy wiper pressure. Results of single disk tests are presented in in Figures 18 to 23 inclusive, and results for multiple disk in Figures 24, 25, and 26. Figures 19, 20, 21, and 22 show the effects of disk immersion depth and disk revolution speed on oil pick-up at slick thicknesses ranging from 0.03 in. to 1.0 in., and Figure 23 is a cross-plot showing the effect of oil slick thickness at a constant disk speed of 0.6 RPS. It is interesting that because of the low specific gravity and low viscosity of the diesel oil there is no oil starving until slick thicknesses of around 0.03 in. are reached. In fact, for 0.25 in. slick thickness and up there is no change of pick-up at a given disk immersion depth.

Figure 24 shows what happens with 5-18 inch diameter disks side-by-side at a spacing of 1.5 inches in a slick thickness of 0.25 inches. Here there is evidence of severe starving in zero current conditions when compared with 4 times the single disk values (only 8 sides wiped with multiple disks).

Figure 25 shows that there is much less evidence of starving when the slick thickness is increased to 1.0 inch.

Figure 26 presents a comparison of simulated waves with smooth water conditions for the battery of 5-18 inch diameter disks with 8 sides wiped, in an oil slick of 0.25 inch thickness. In waves 5 inches high with a 1.6 second period and disk immersion depth 0.5 in., there was about 25% greater total oil pickup than with a static disk immersion depth of 6 inches. However, the simulated wave test may have been unrealistic in that the confined trough tended to pump the oil towards the disks, and due to its light weight diesel oil does not entrain with the water.

Once the wiper problem had been solved, the diesel tests were easy to conduct and collection was precise, giving very little data scatter. However, the actual quantities picked up in a given time were only about a quarter of the pick-up with 40 weight oil. Only negligible quantities of water were picked up with the diesel oil.

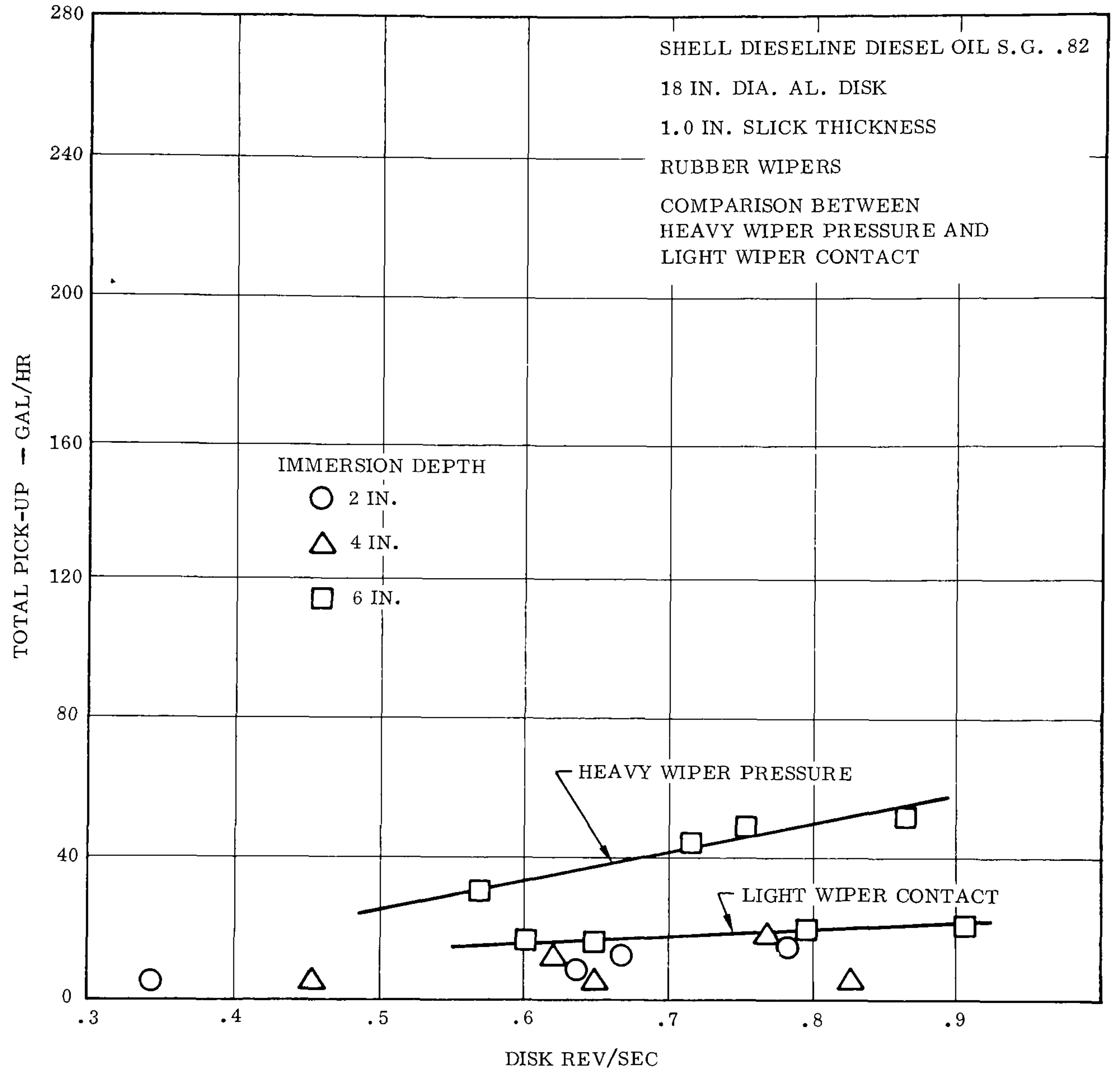


Figure 18. Zero Current Oil Recovery Tests

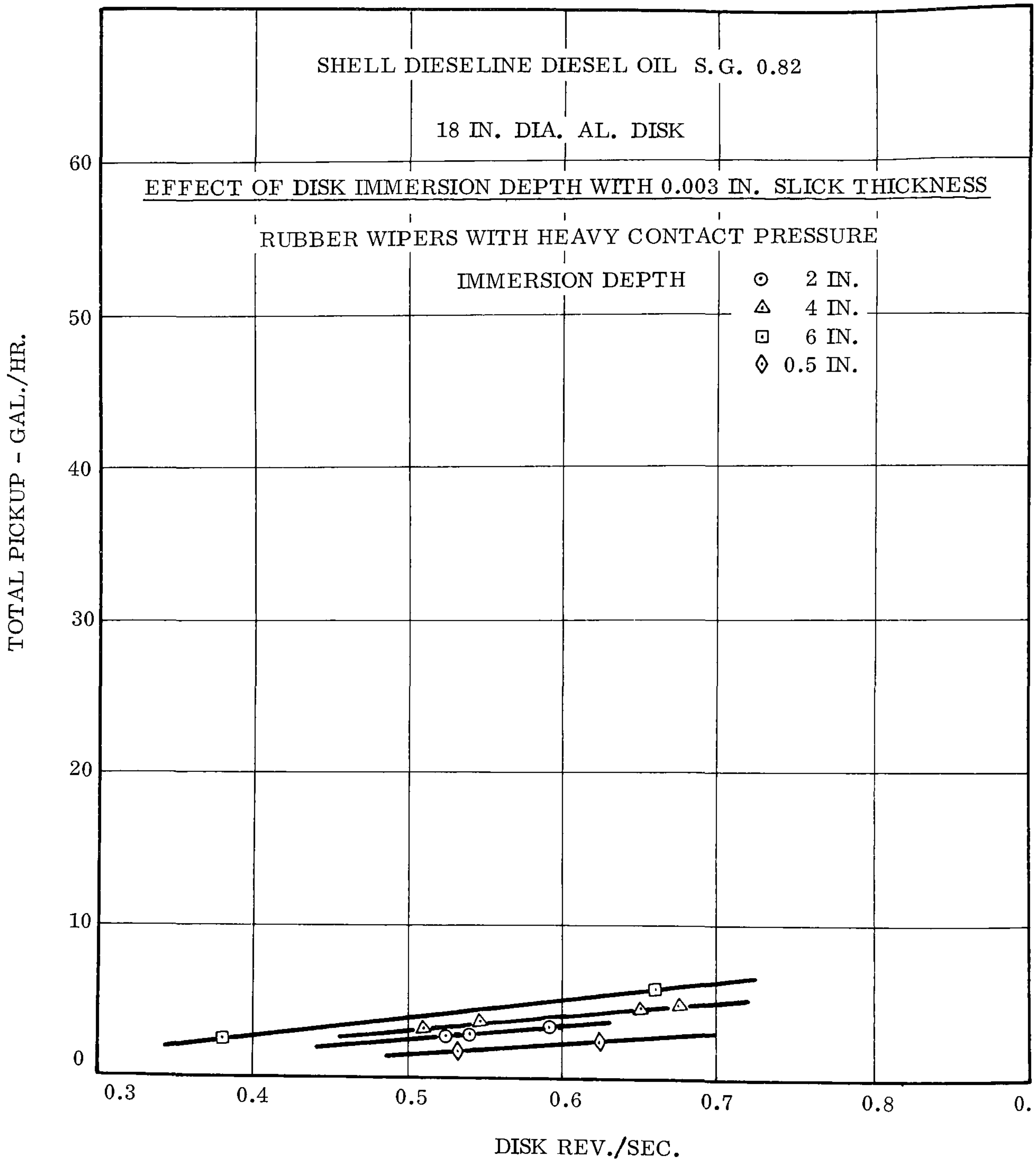


Figure 19. Zero Current Oil Recovery Tests

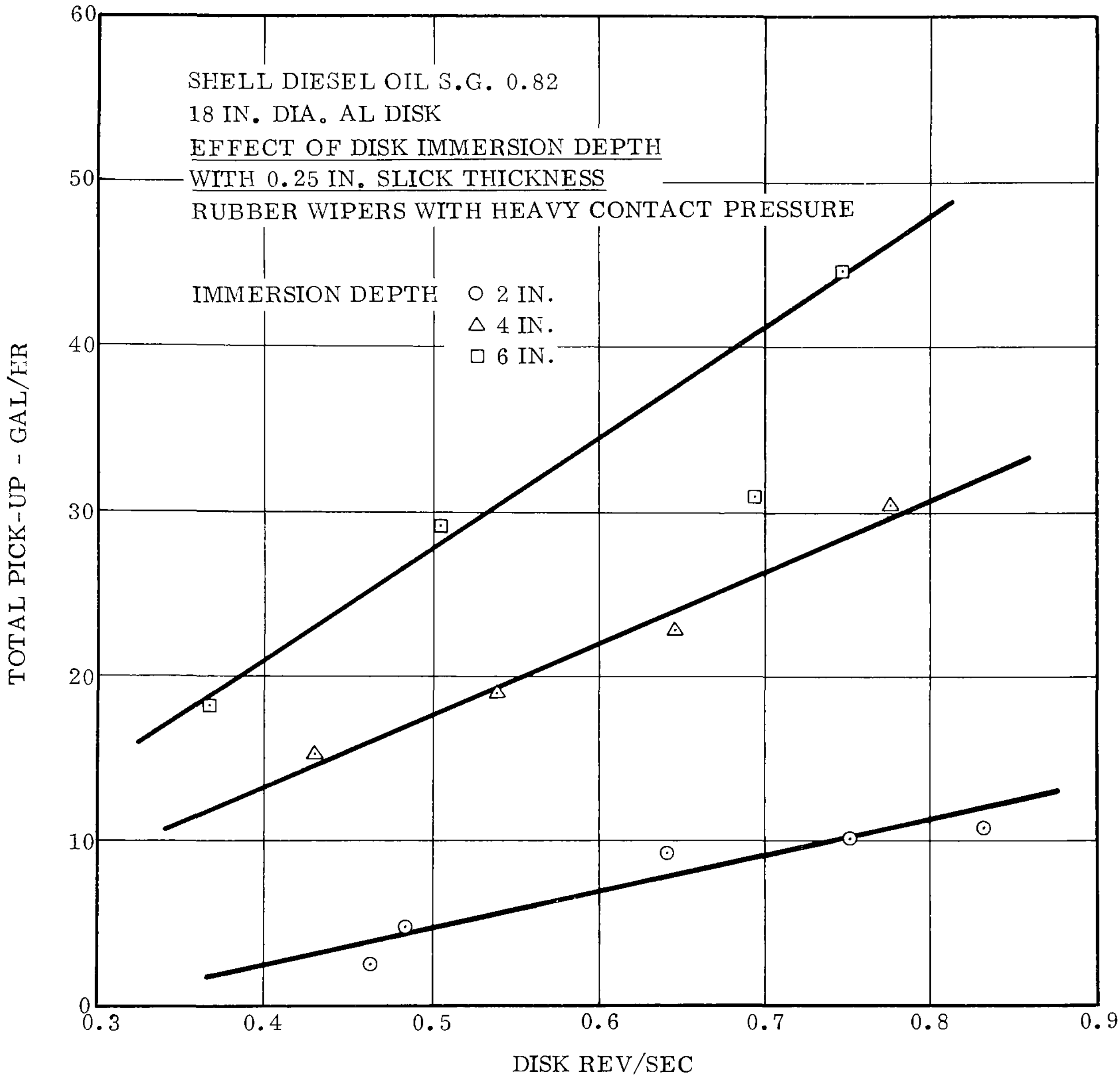


Figure 20. Zero Current Oil Recovery Tests

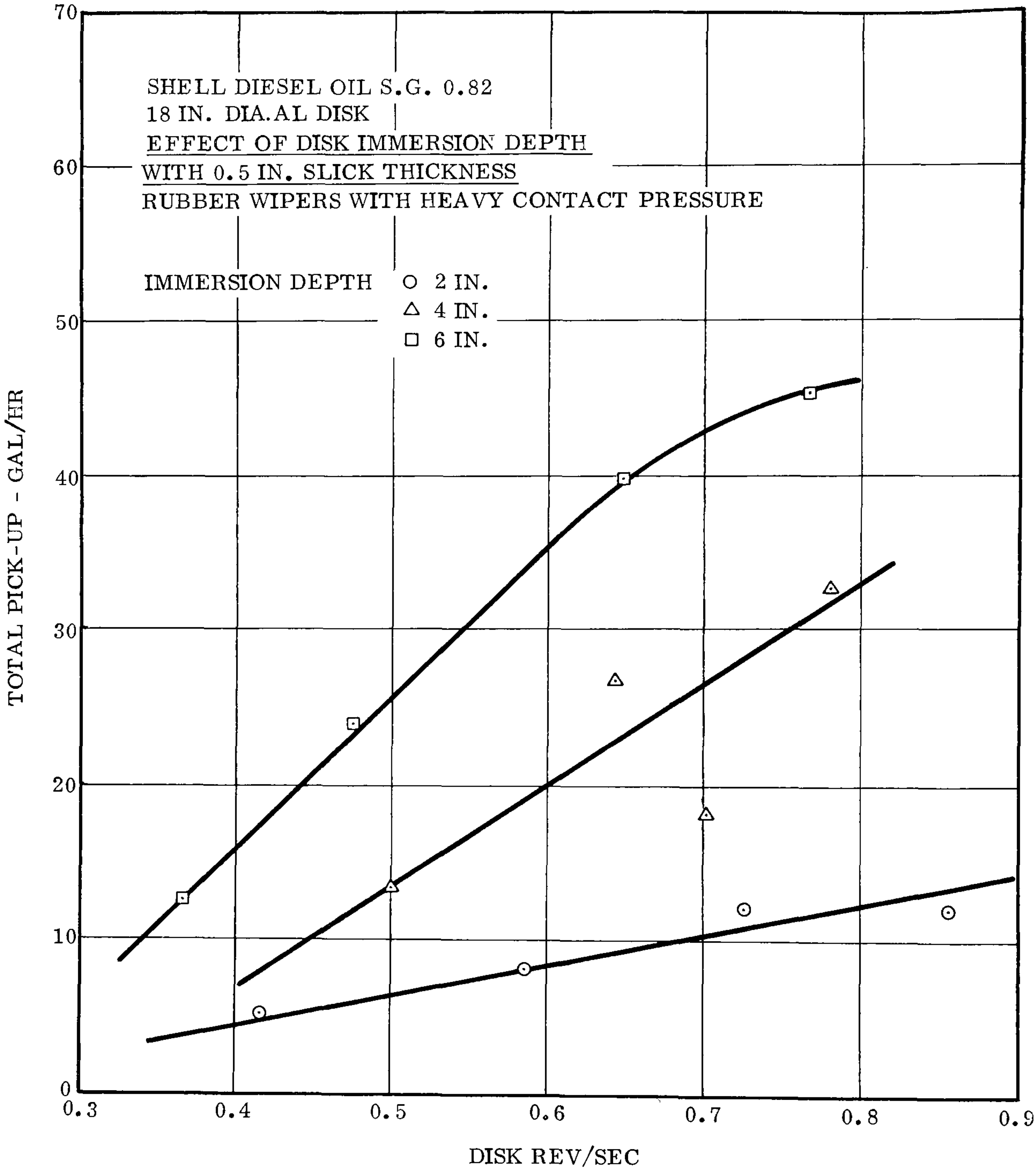


Figure 21. Zero Current Oil Recovery Tests

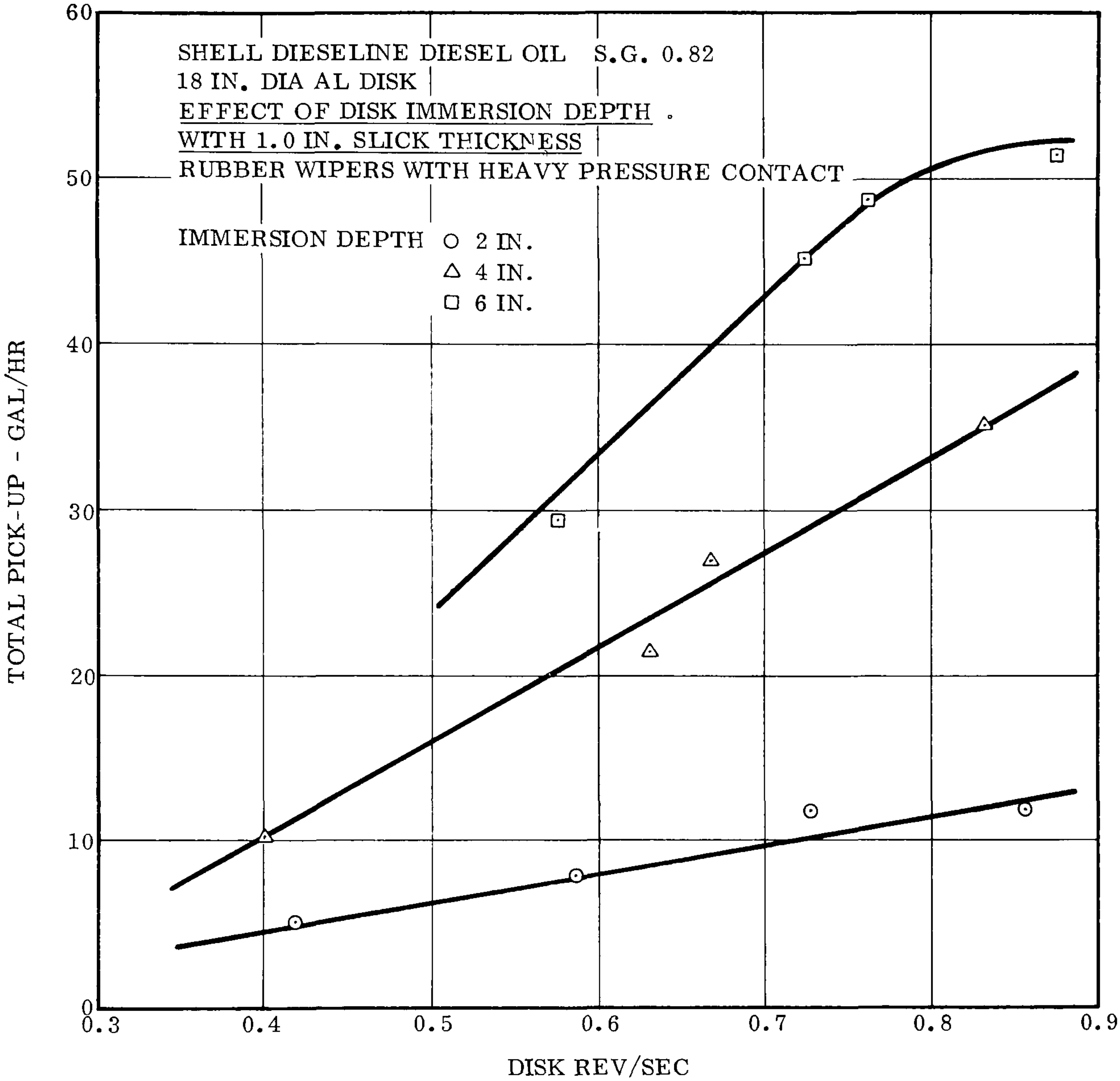


Figure 22. Zero Current Oil Recovery Tests

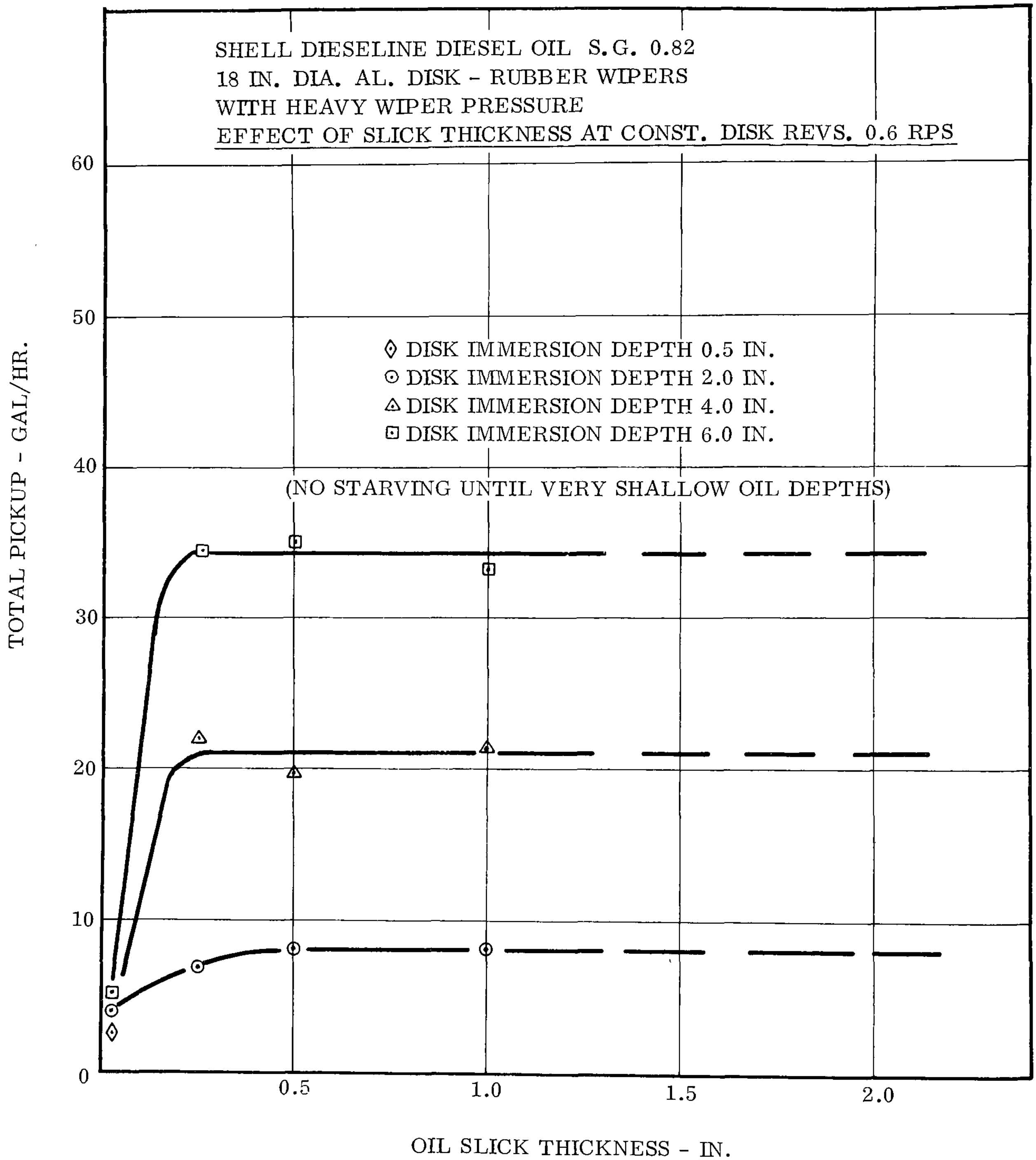


Figure 23. Zero Current Oil Recovery Tests

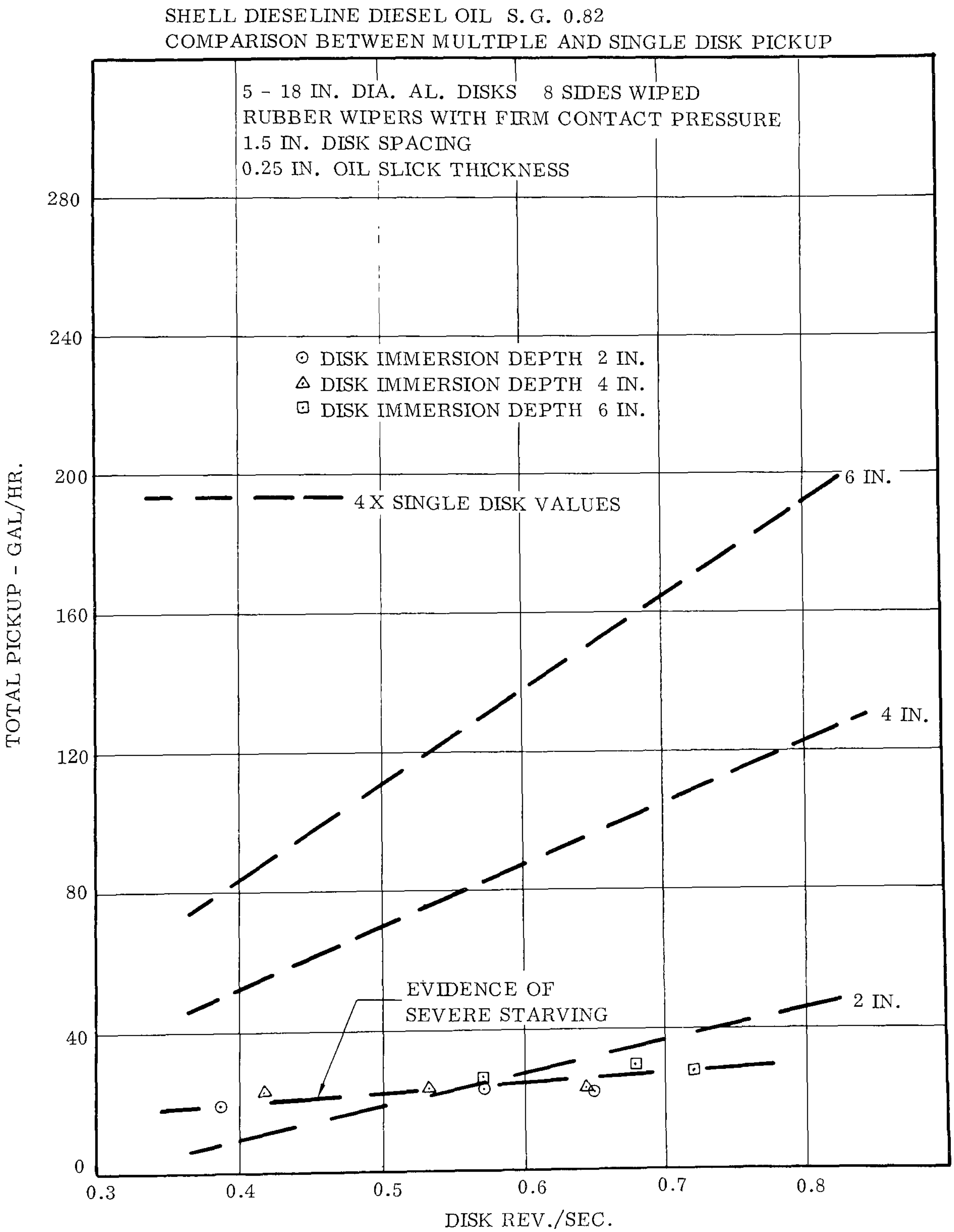


Figure 24. Zero Current Oil Recovery Tests

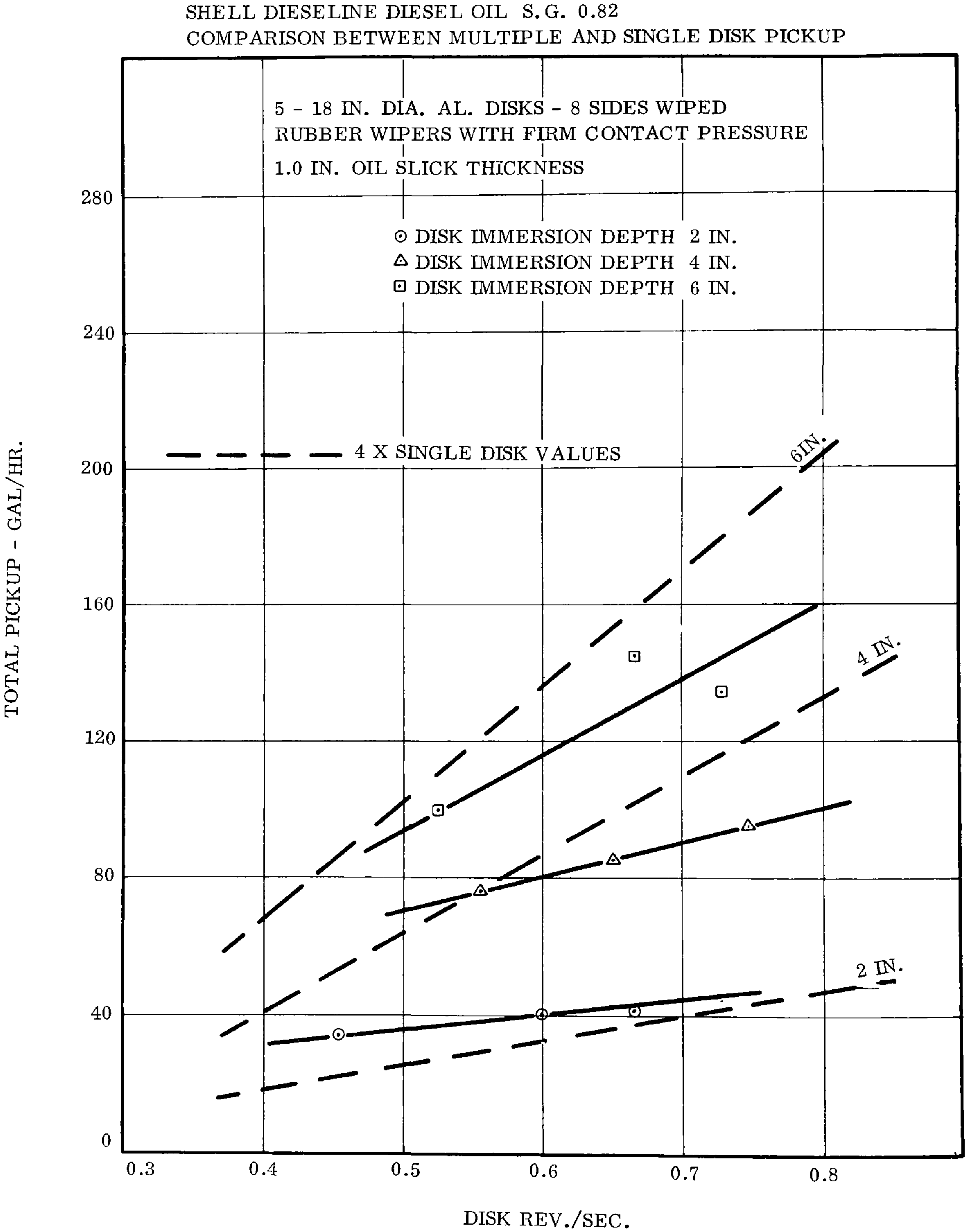


Figure 25. Zero Current Oil Recovery Tests

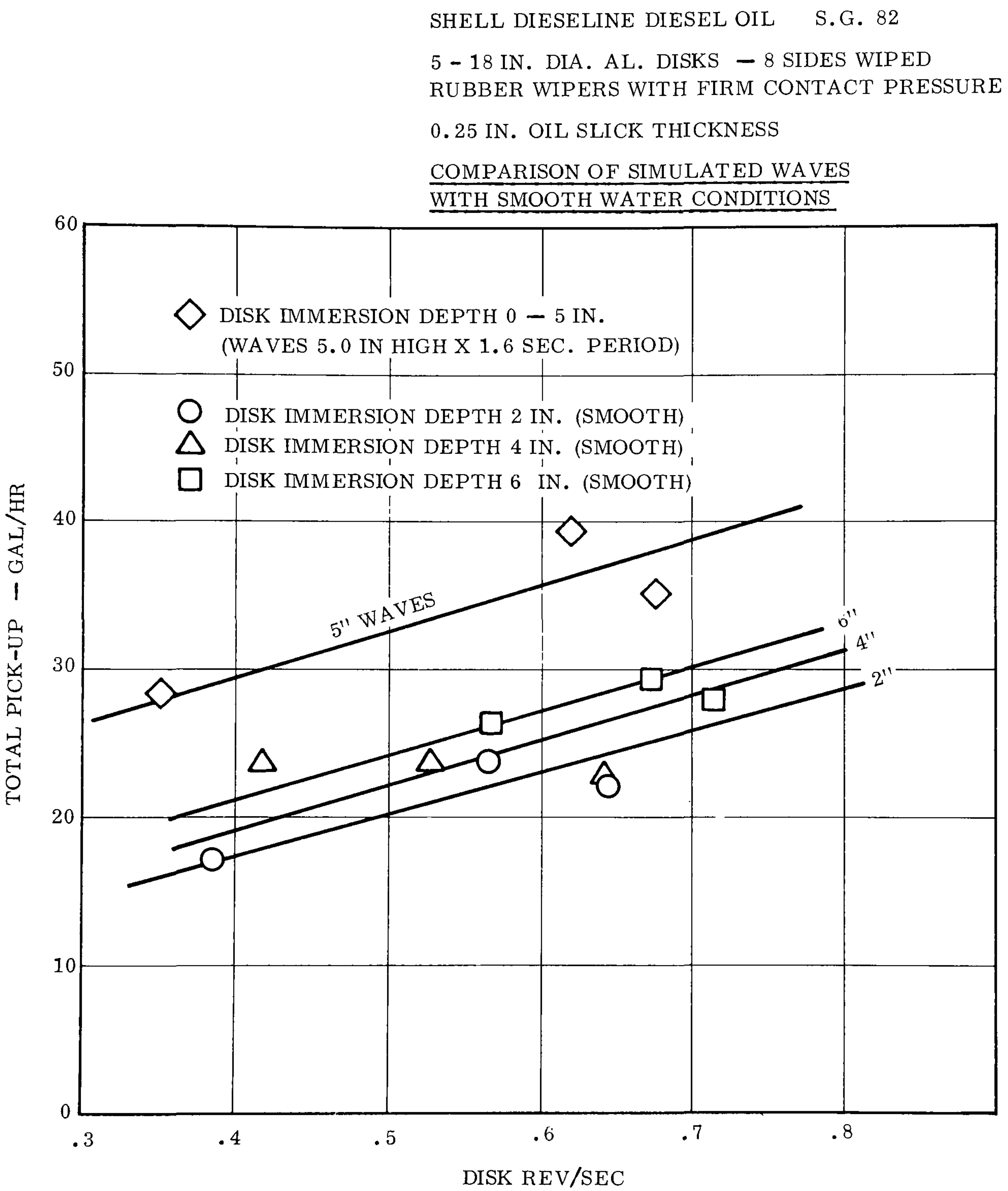


Figure 26. Zero Current Oil Recovery Tests

3. Oil Type-Bunker 'C' Fuel Oil

This was the most difficult of all the oils to work with in that it weathered very quickly into a heavy black tar, quickly gumming up the apparatus. In addition there was evidence of very severe oil starving, even with a single disk. It was obvious that about twice as much oil was being picked up on the disk side away from the mirror box, and so this box was removed. Measurements of quantities collected were imprecise because flow could not suddenly be shut off. Although large quantities of oil were picked up, water content was high due to bubbles of water being encapsulated by the oil. Measurement of water content was inprecise due to the black tar coating the insides of the transparent plastic buckets. Oil slick thickness quoted is not that near the disk, as the rotating disk produced a hole in the underside of the oil. However, a certain amount of test data was obtained for the single disk, and this is plotted in Figures 27 to 34 inclusive. Wiper gap was standardized at 0.025 in. Figures 27, 28, 29, 30, and 31 show the effect of slick thickness, far from the disk, on pick-up, for a range of disk speeds and immersion depths. Oil starving is evident, particularly at the higher disk pseeds in a slick thickness of 1.7 inches. Figure 32 is a cross-plot showing the effect of slick thickness at a constant disk speed of 0.6 RPS. for the 18 inch diameter aluminum disk. Here starving is evident at the lower slick thicknesses.

Figure 33 shows the total pick-up for a 12 inch diameter disk in an approximate slick thickness of 1.0 inch. For this test the oil had "weathered" and the mirror box was removed for better inflow to the disk.

The pick-up for an immersion depth of 4.0 in. was about 20% greater than for an earlier test on the 18 inch disk at an immersion depth of 6.0 in., see Figure 30.

Figure 34 is a plot of the water content in the pick-up as a percentage of the total pick-up. Although there is a great deal of scatter in the data, it is clear that disk speeds will have to be lower than 0.1 revolutions per second in order to have water content of the picked up oil less than 10%. This is lower than the speeds that were tested. One significant thing that was noticed about the Bunker 'C' oil is that it "puddles" and does not spread, probably due to its high density combined with its high viscosity

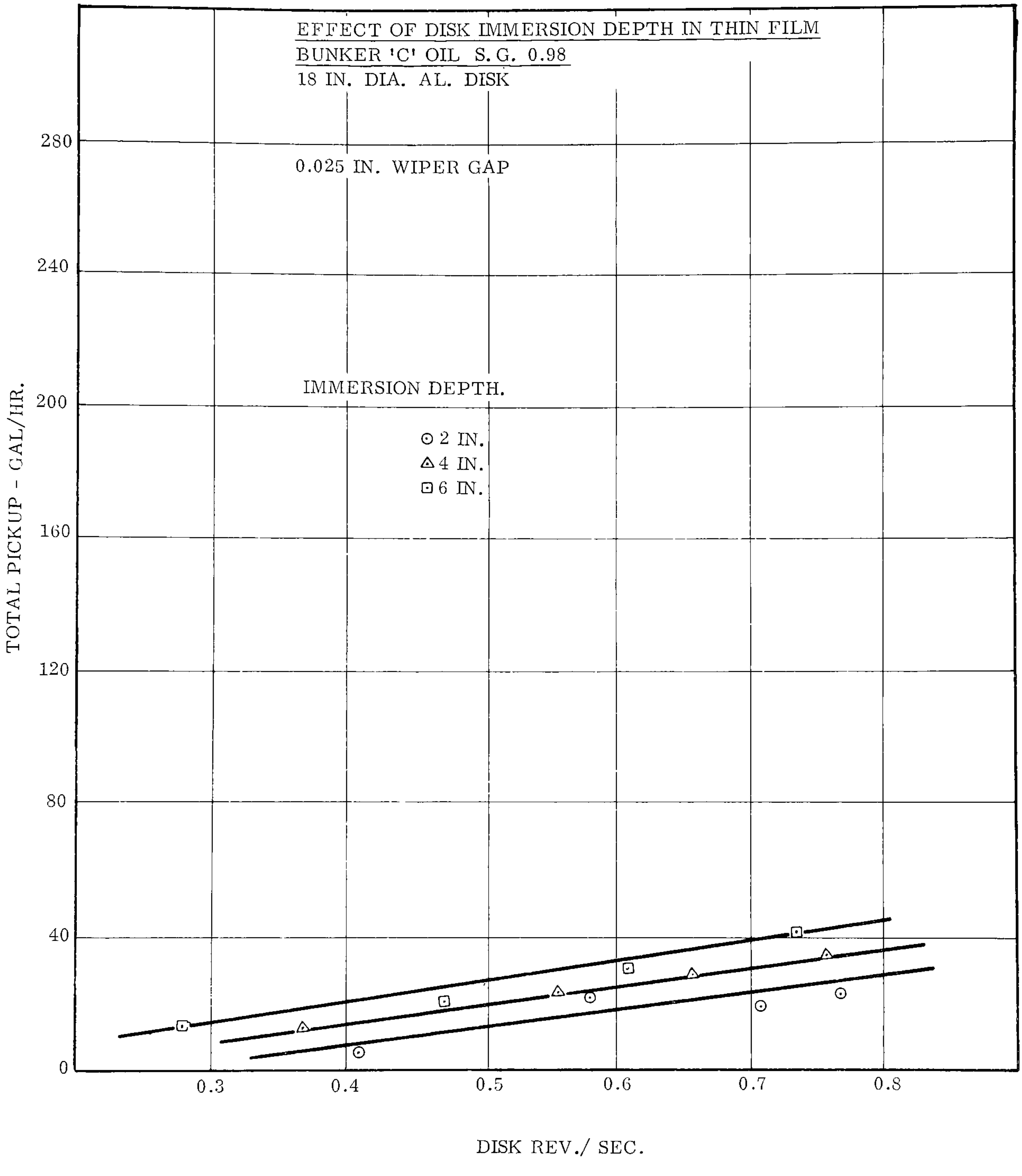


Figure 27. Zero Current Oil Recovery Tests

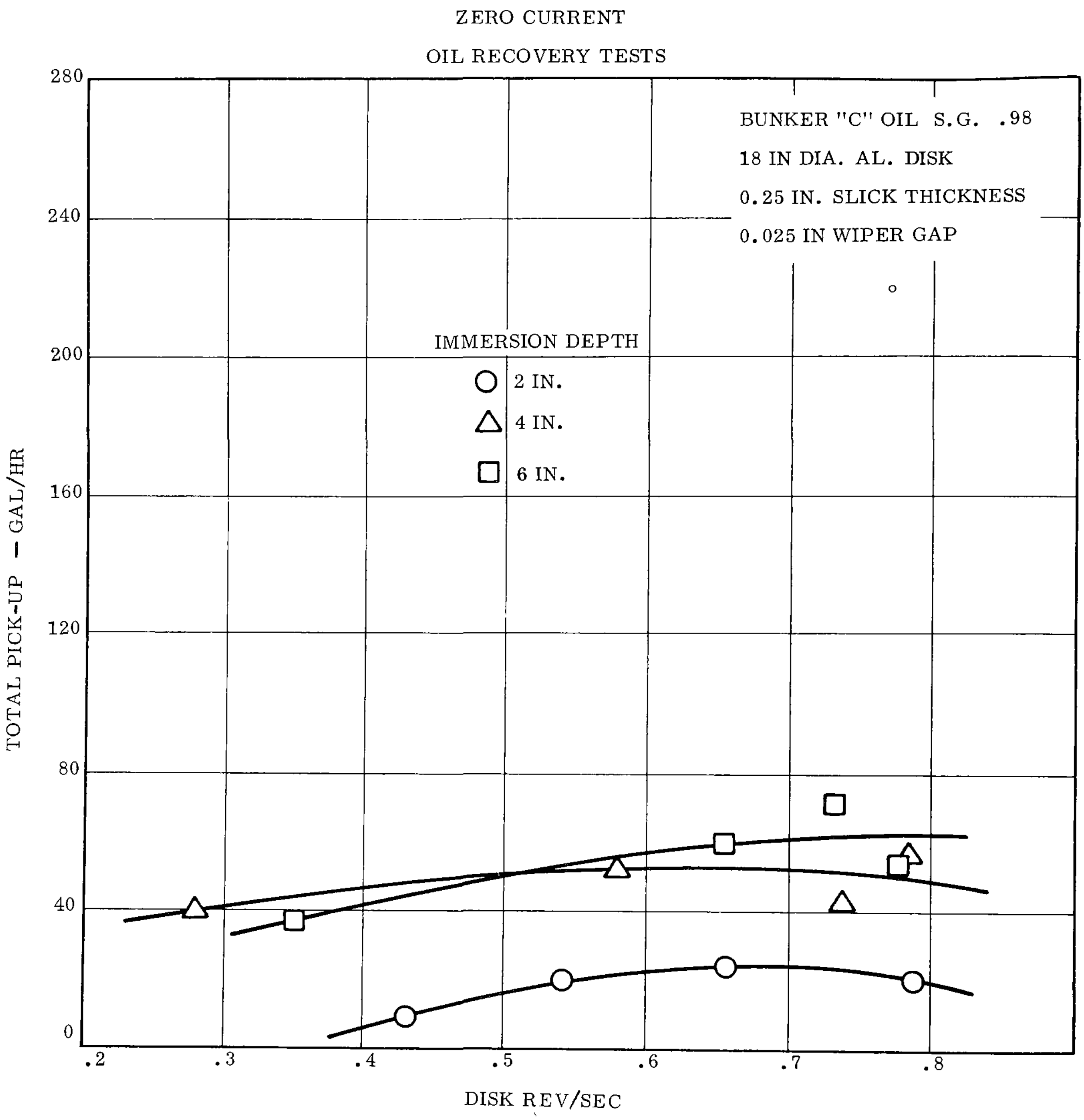


Figure 28. Zero Current Oil Recovery Tests

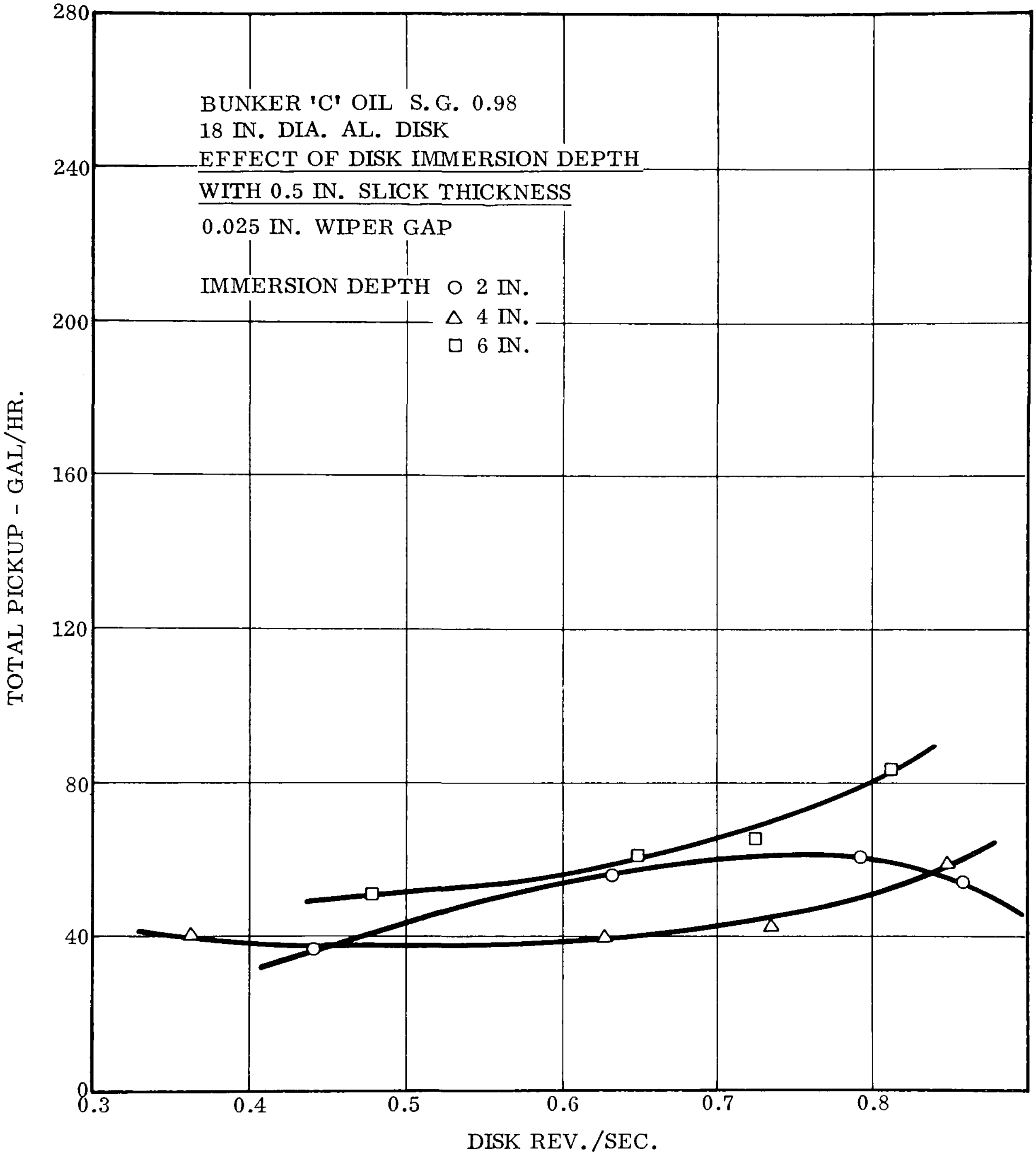


Figure 29. Zero Current Oil Recovery Tests

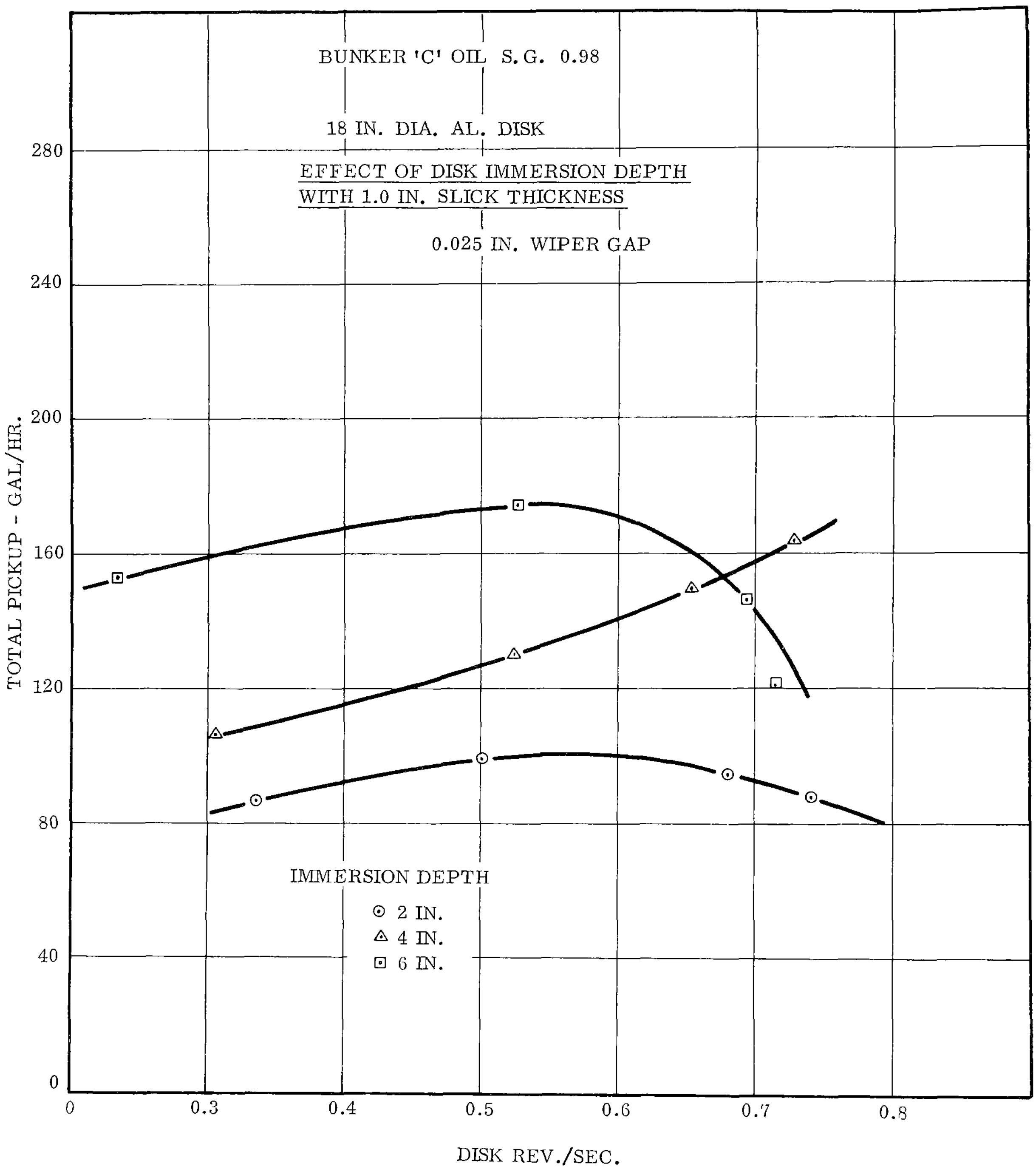


Figure 30. Zero Current Oil Recovery Tests

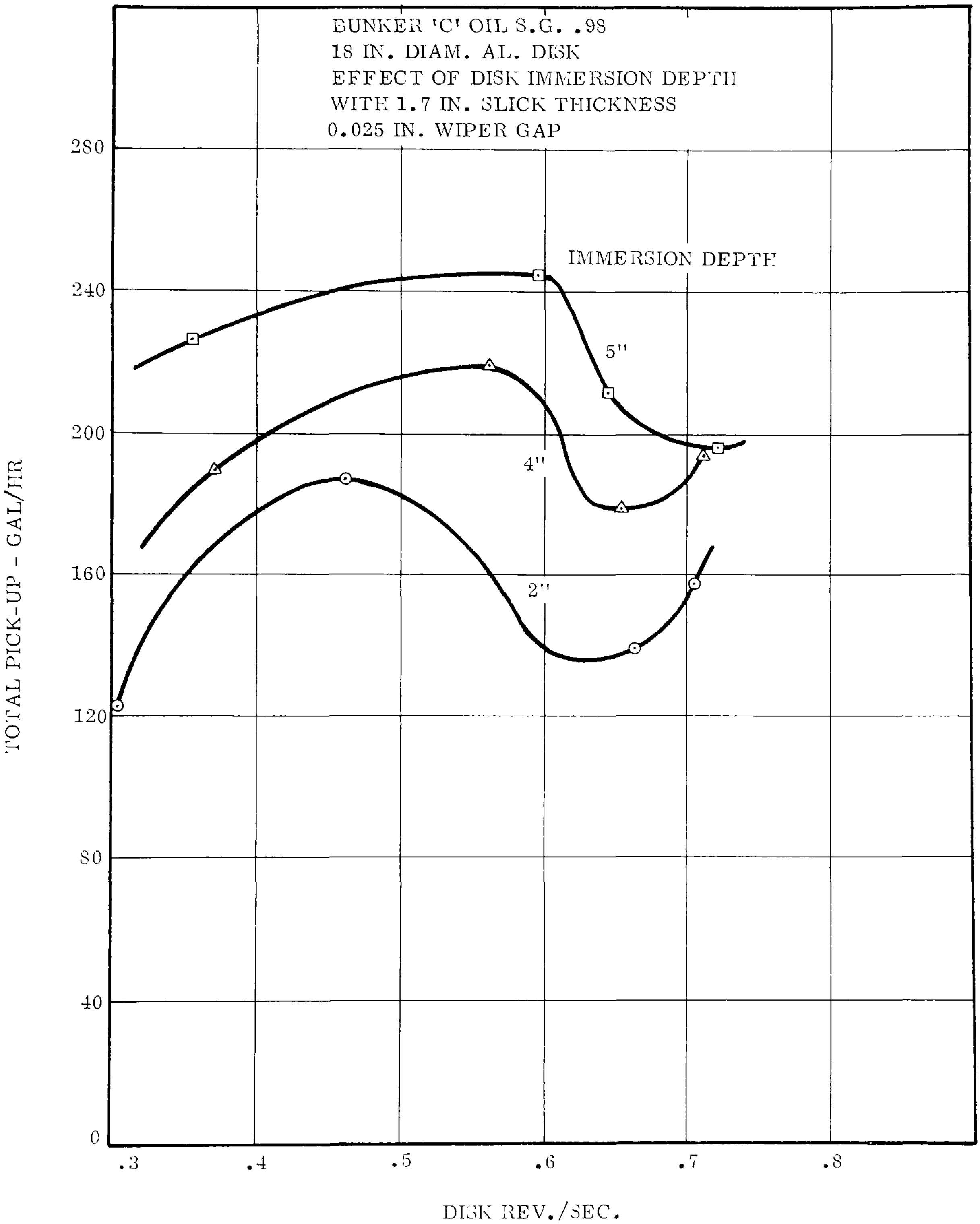


Figure 31. Zero Current Oil Recovery Tests

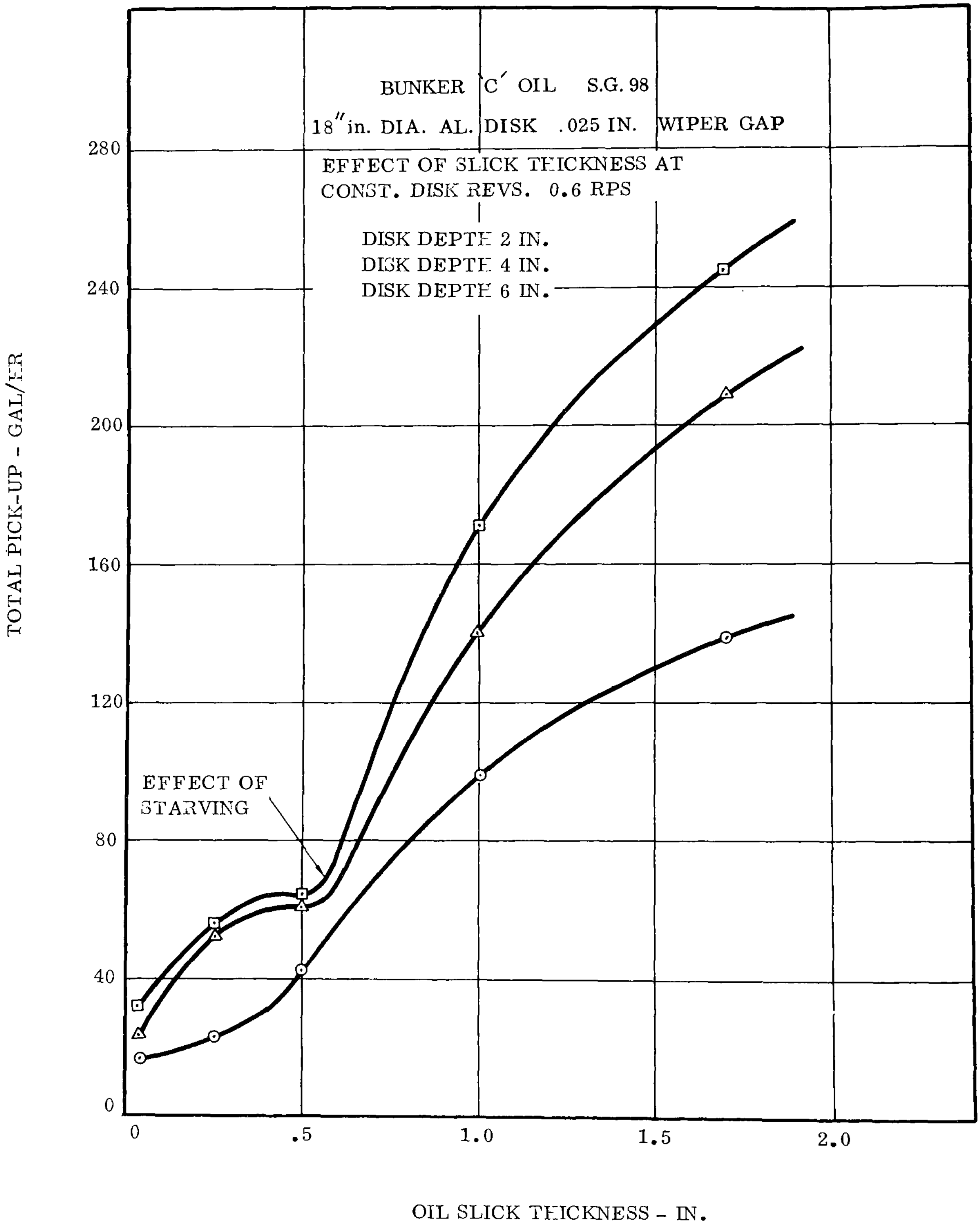


Figure 32. Zero Current Oil Recovery Tests

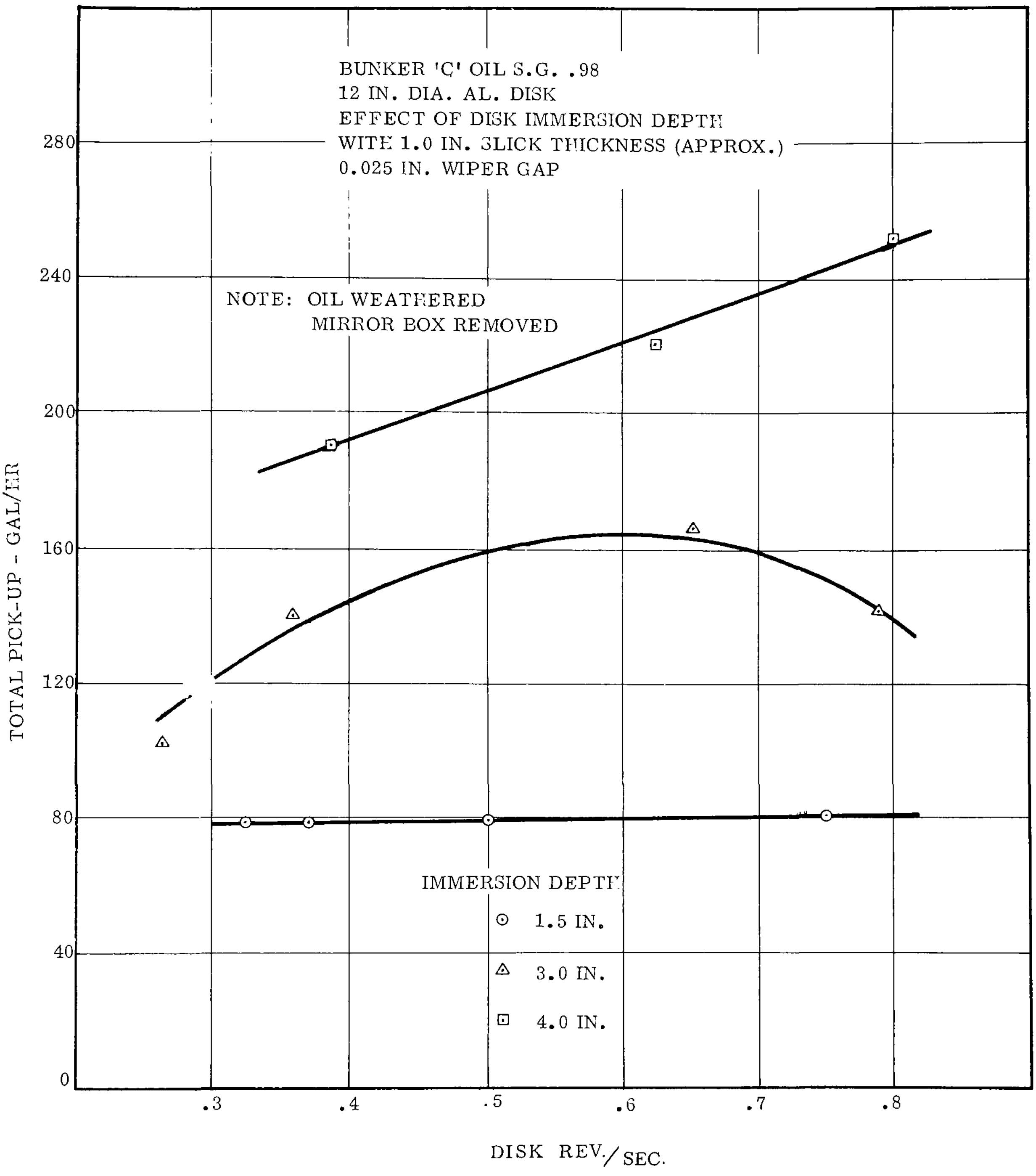


Figure 33. Zero Current Oil Recovery Tests

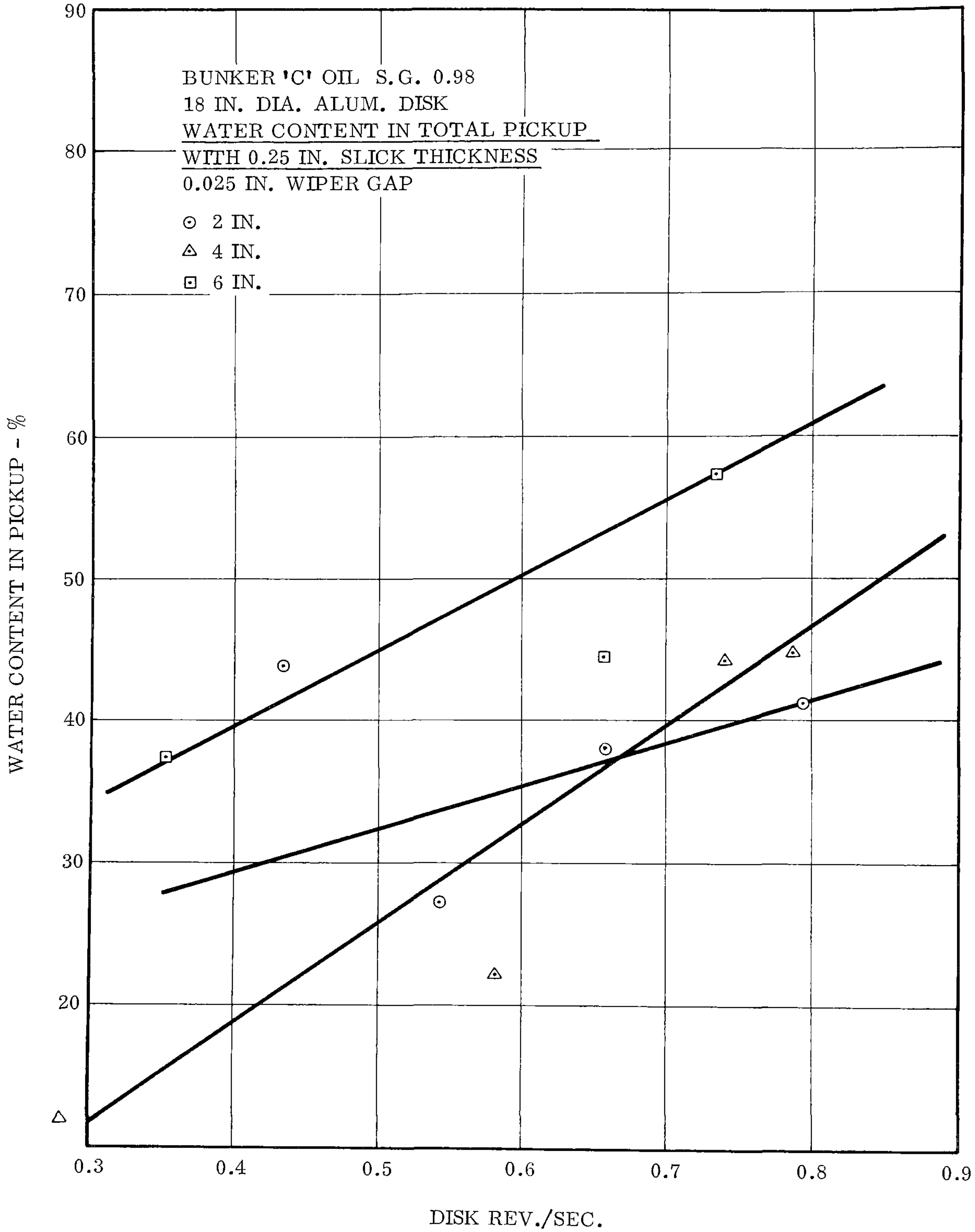


Figure 34. Zero Current Oil Recovery Tests

TESTS IN A 300 FOOT TOWING BASIN

A total of 216 test runs were carried out for this series of tests. 177 of these runs were made with SAE 40 weight motor oil in smooth water. 9 runs were made in waves combined with current with 40 weight oil. 30 runs were made with Bunker 'C' oil in smooth water.

The main purpose of the tests was to find the effect of current and disk spacing on the oil pick-up rate of a multi-disk system, and to find the best direction of disk rotation relative to the current. The data collected is plotted in Figures 35 to 53 inclusive.

Figures 35 and 36 show the results for tests run with the disks rotating both with and against the current to determine the best operating condition for all subsequent tests. The test conditions were oil thickness 0.25 in., disk spacing 1.5 inches, and disk immersion depth for the 5-18 inch diameter disks 6.0 inches. It was established conclusively that the disk should rotate with the current for minimum relative velocity, rather than against the current for maximum relative velocity. All subsequent testing was conducted with the disks rotating with the current.

The first few tests runs were performed with the five disks spaced at 1-1/2 inches between disks and with six inch immersion into the liquid. All five disks were wiped on a total of ten sides, and the quantities collected. After this all following tests were conducted with the center disk providing the test sample and the other four disks being wiped and the liquid then discharged downstream of the disk/liquid interface.

Figure 37 is a plot of Total Pick-up versus disk revolutions for a series of current speeds for an oil slick thickness of 0.25 inch. Disk spacing was 1.5 inches and disk immersion depth 6.0 inches. Also laid on this graph is the appropriate zero current line from tests in the ten foot trough. The maximum current speed was 3.0 knots and this was combined with excessive disk revolutions up to 2.2 revs./sec. resulting in a much reduced pick-up. At disk rates of 2 c.p.s., water was thrown everywhere, including over the test personnel; subsequent tests were performed at disk rates of 1.5 c.p.s. maximum. A cross-plot of this graph at constant disk revs. of 0.8/sec. (Figure 48) shows maximum pick-up at a current speed of 2 knots, followed by a very rapid fall off. Large quantities of water were collected under all test conditions.

Figures 38, 39, and 40 cover conditions where disk spacing was increased to 3.0 inches and oil thickness to 1.0 inches. Selected runs were made at three immersion depths; six, four, and two inches. Also laid on these three figures are the zero current lines from tests in the 10 foot trough. Cross-plots of these graphs at constant disk revs. of 0.8 per sec. are given in Figure 47. At an immersion depth of 6.0 inches, maximum pick-up is at 2 knots, followed by a very rapid fall off with increasing current, as before.

At 2 inches immersion depth current speed seems to have little effect on pick-up between zero and three knots. Again, large quantities of water were noted in test samples at four and six inch immersion. An attempt was made to conduct test runs at high current speeds in excess of 3 knots, without success. The test time was too short and in addition the water would spill into the mirror box.

Figures 41, 42, 43, and 44 cover conditions with disk spacing 1.5 inches and oil thickness 1.0 inches. For the data on Figure 42 the test fixture was modified to add a deflector blade on either side of the center (test) disk. This deflector was a wedge 1/2 inch thick, with a three inch chord and a seven inch span. The deflectors were installed in such a fashion that the trailing edge of the wedge was flush with the trailing (or downstream) edge of the disks. The wedges were placed so as to completely penetrate the oil layer at all immersion depths.

Five test runs were made during which it was noted that there appeared to be excessive drainage into the test disk from the oil wiped off the adjacent disks. A barrier was added to channel the oil away from the center disk and the test series was continued. After fourteen runs the two deflectors were removed from the test fixture and test runs were repeated at four inch immersion to assess the effectiveness of the deflectors. The test data was erratic and inconclusive.

It is noted that the three inch disk spacing was more effective than the 1-1/2 inch spacing for a given set of operating conditions, See Figure 49.

Oil condition SAE 40 weight two inch thick, was disks spaced three inches apart at an immersion depth of 6.0 inches, yielded the results of Figure 45. Selected runs were made at all three immersion depths in an attempt to obtain a correlation with the previous run series. It was noted that at this oil thickness the recovery was rather incomplete in that there was very little clean up except at high immersion depths, current speeds and disk rates. In most runs the water content of the samples was quite low.

Data for oil condition SAE 40 weight, three inch thick, disks spaced at 1-1/8 inches apart and set to a depth of 6.0 inches is plotted in Figure 46. Water content of the samples was very high.

Oil condition SAE 40 weight one inch thick, disks spaced at 1-1/2 inches apart. This test series was a repeat of the previous series with the addition of wave action to the test environment. Runs were made at four inch and two inch immersion depths, see Figures 50 and 51 respectively. The ability of the system to recover oil was definitely reduced at the two inch depth, but was increased at the four inch depth. The wave height was approximately two inches and the period something less than one second.

OIL CONDITION BUNKER 'C', APPROXIMATELY 0.8 INCHES THICK AND DISK SPACING 1.5 INCH.

At the six inch immersion depth there was an excessive amount of oil collected, and spilling occurred out of the collection trough. At four inch immersion (see Figure 52) the test could handle the oil but test data was very erratic and inconclusive. It was determined that the Bunker 'C' oil is so viscous that in some instances, the collection pan, which is a reference volume, does not fill completely at time of overflow. The collection rate is therefore in error. This error is amplified at high discharge rates. The solution to the problem was to tilt the collection pan to aid the oil flow to ensure complete filling during sampling time. This was done on runs 208 through 216 for a two inch immersion depth (see Figure 53). The data obtained on these runs is quite reliable. The data on Figures 52 and 53 shows evidence of a high degree of oil starving at the higher disk revolutions. The Figures indicate that disk revolutions should be lower than 0.4 revs./sec. with 18 inch diameter disks in order to avoid starvation.

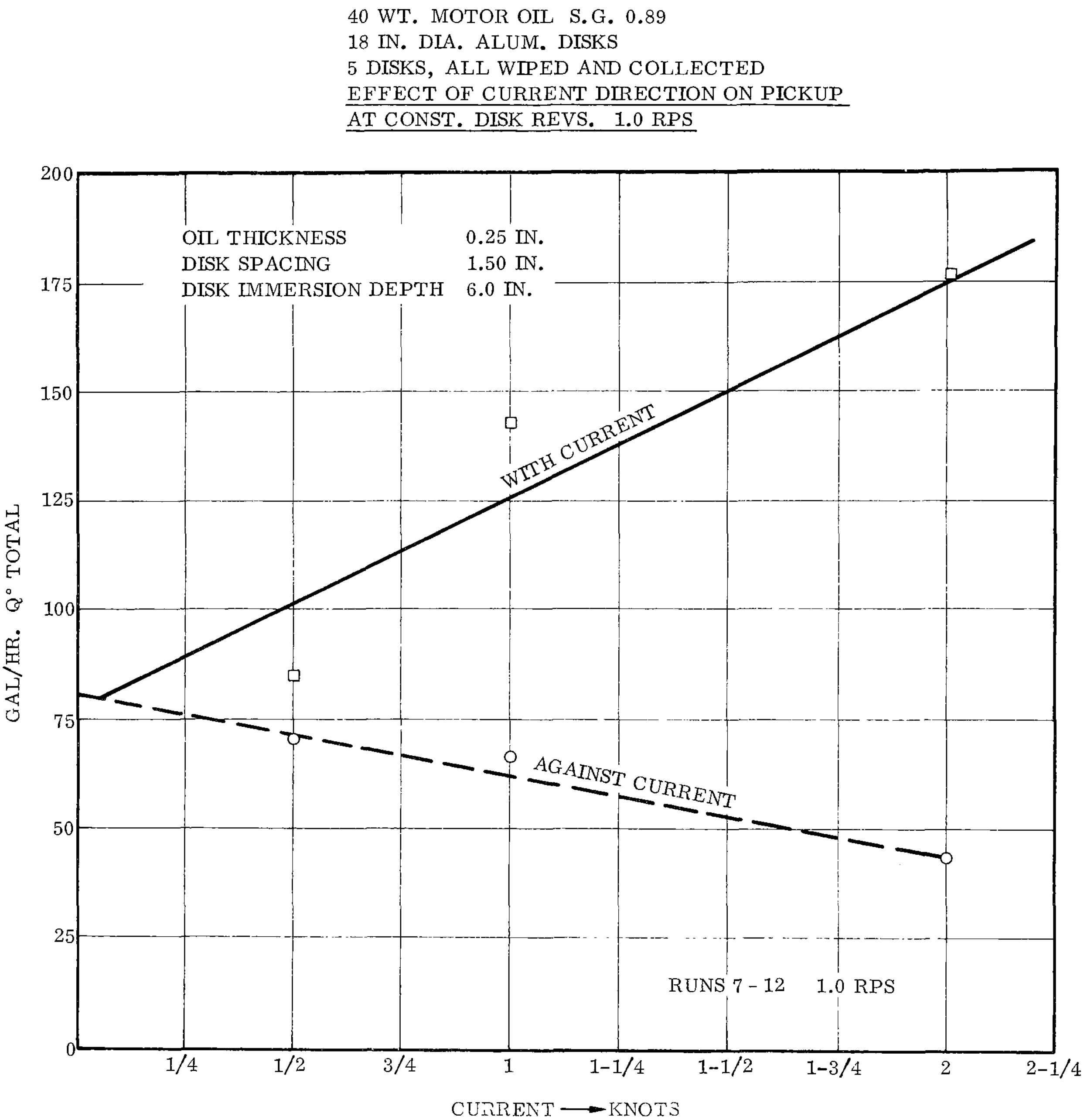


Figure 35. Oil Recovery Tests Smooth Water - Current Conditions

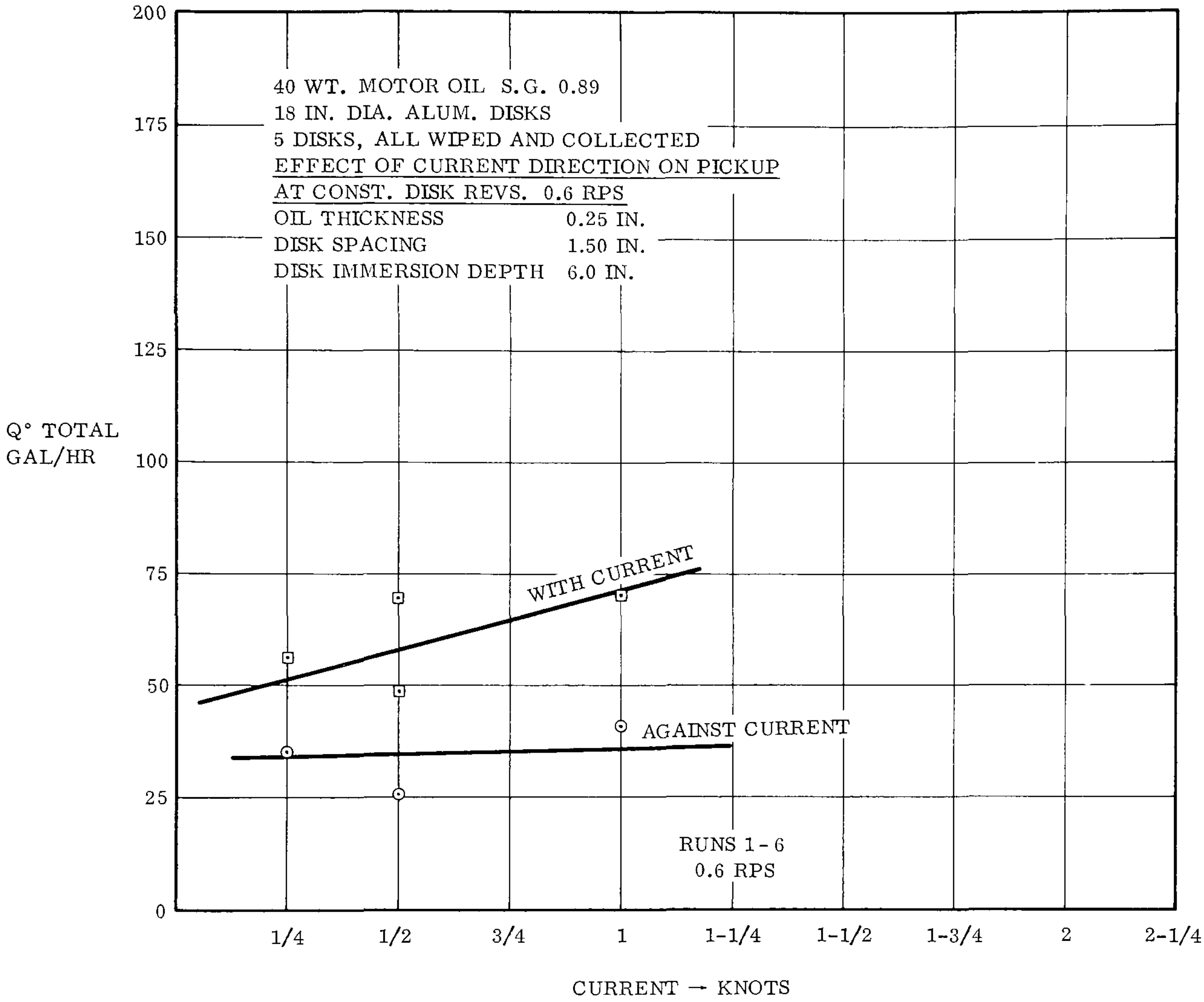


Figure 36. Oil Recovery Tests Smooth Water - Current Conditions

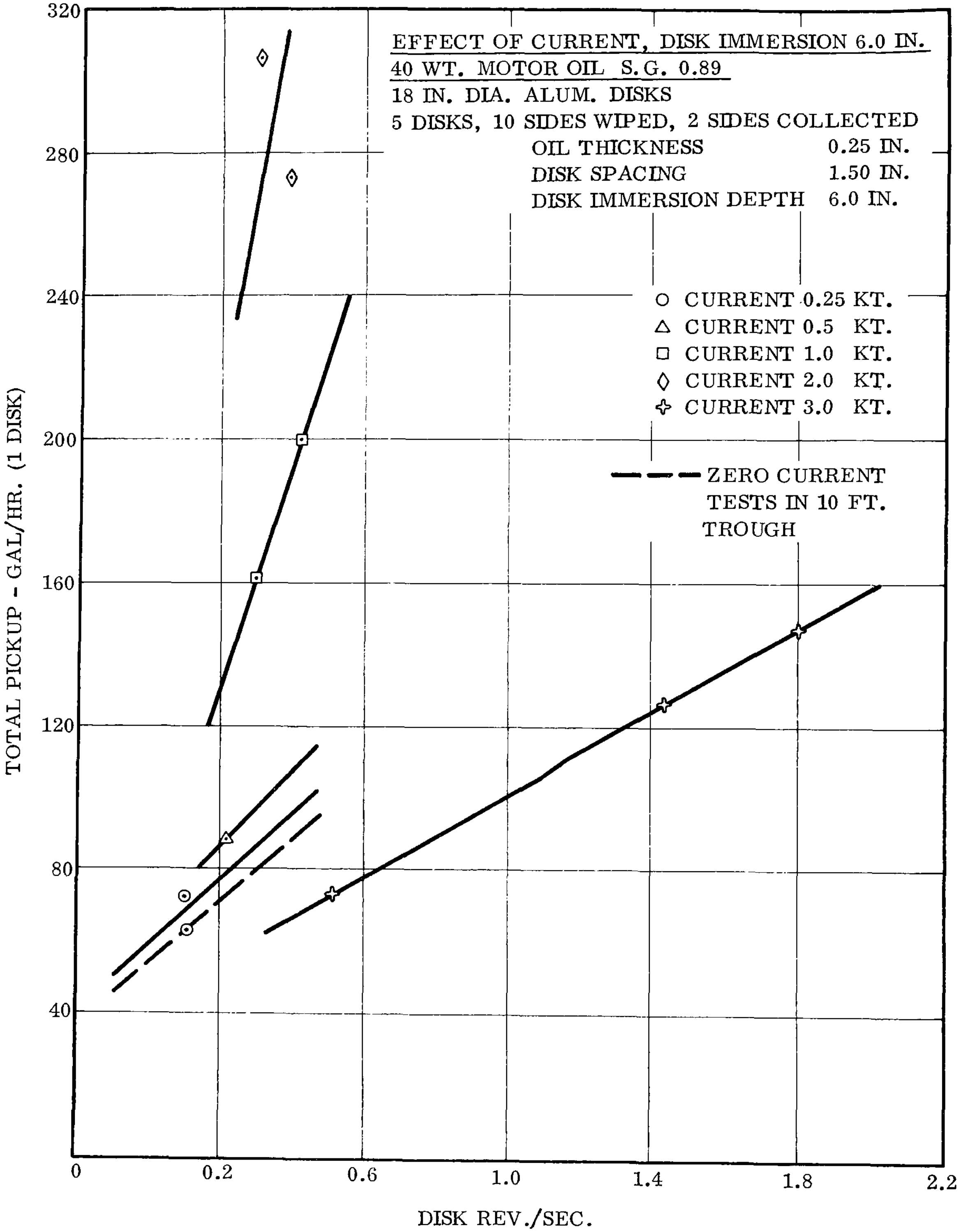


Figure 37. Oil Recovery Tests - Current Conditions

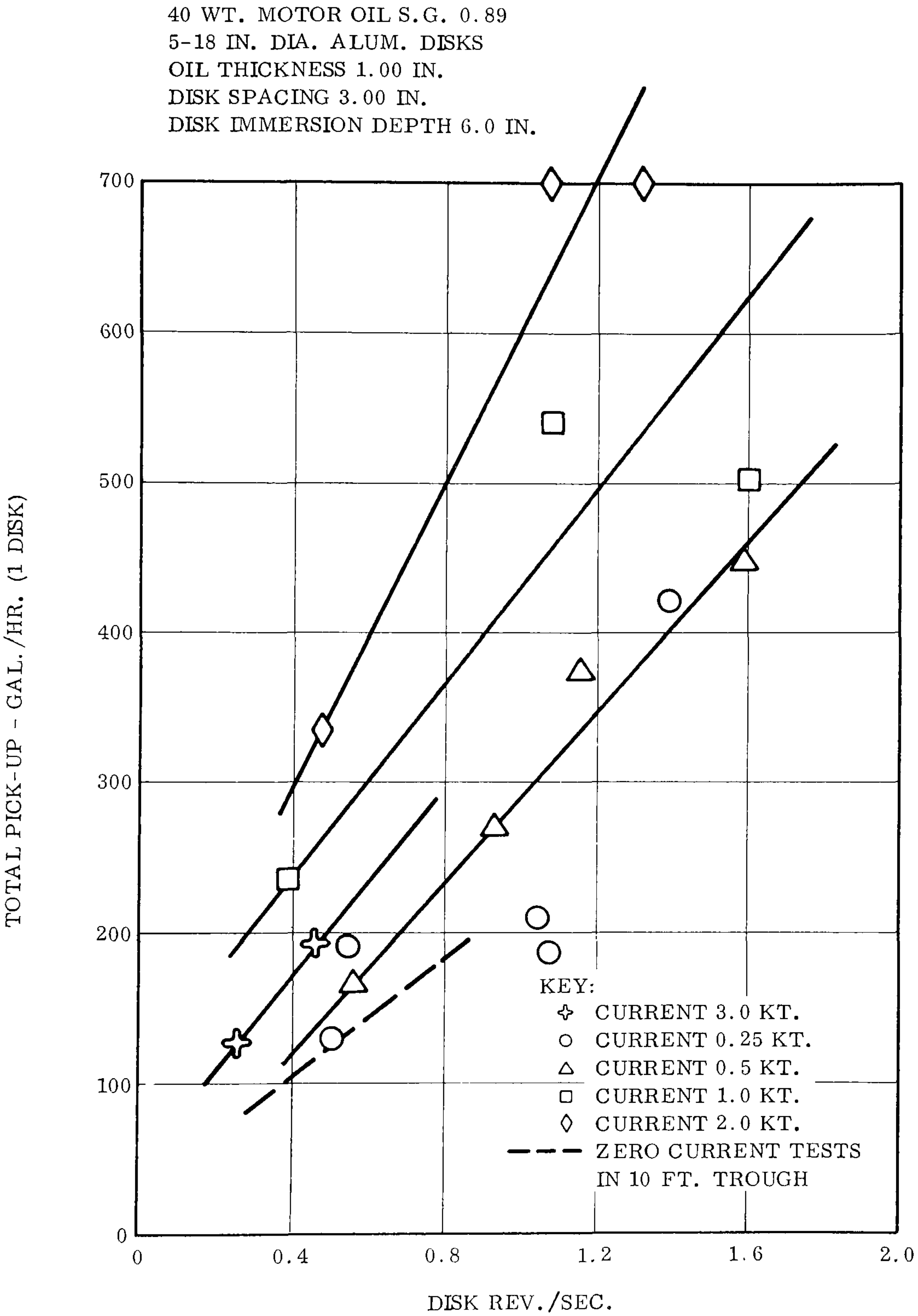


Figure 38. Oil Recovery Tests - Current Conditions

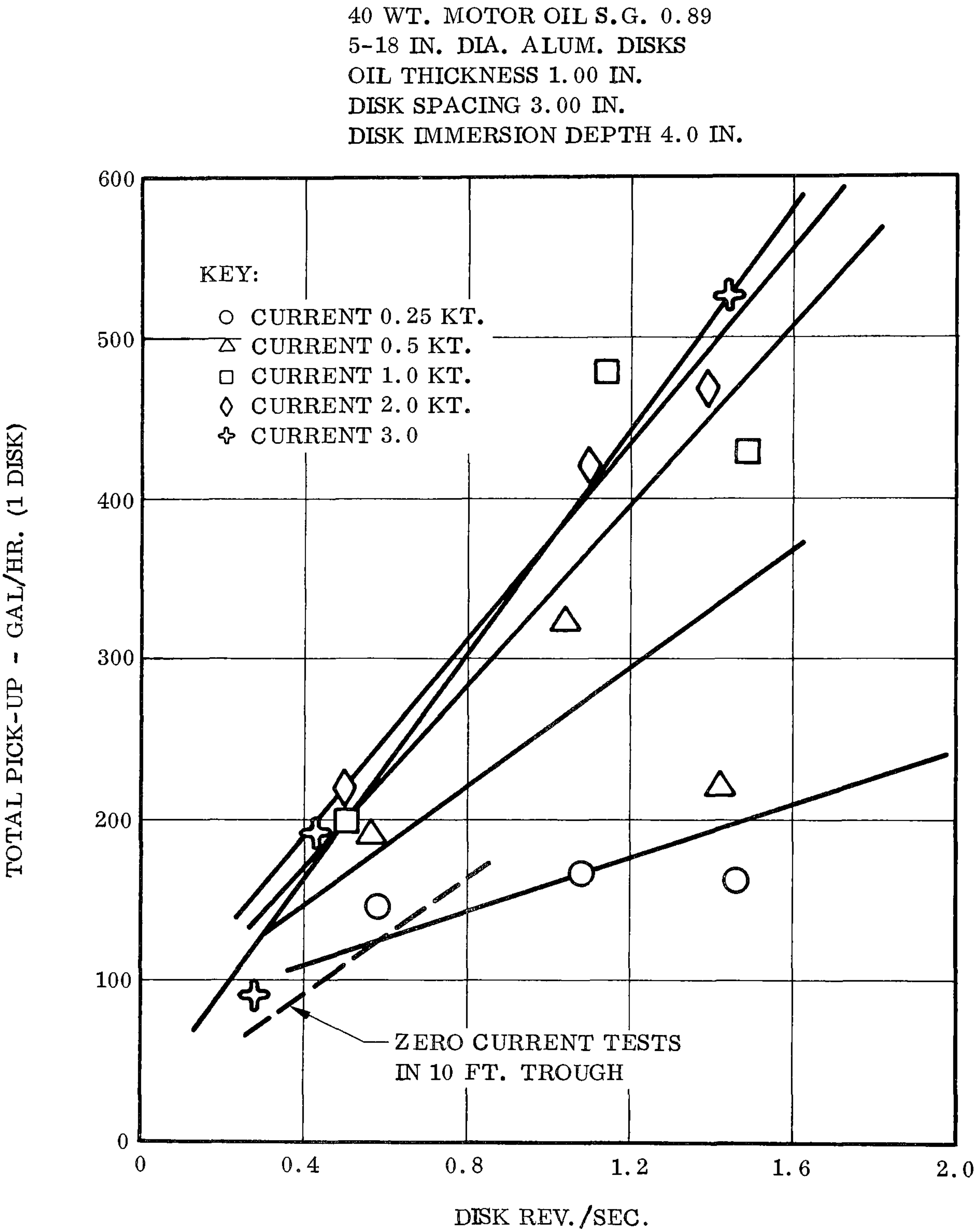


Figure 39. Oil Recovery Tests - Current Conditions

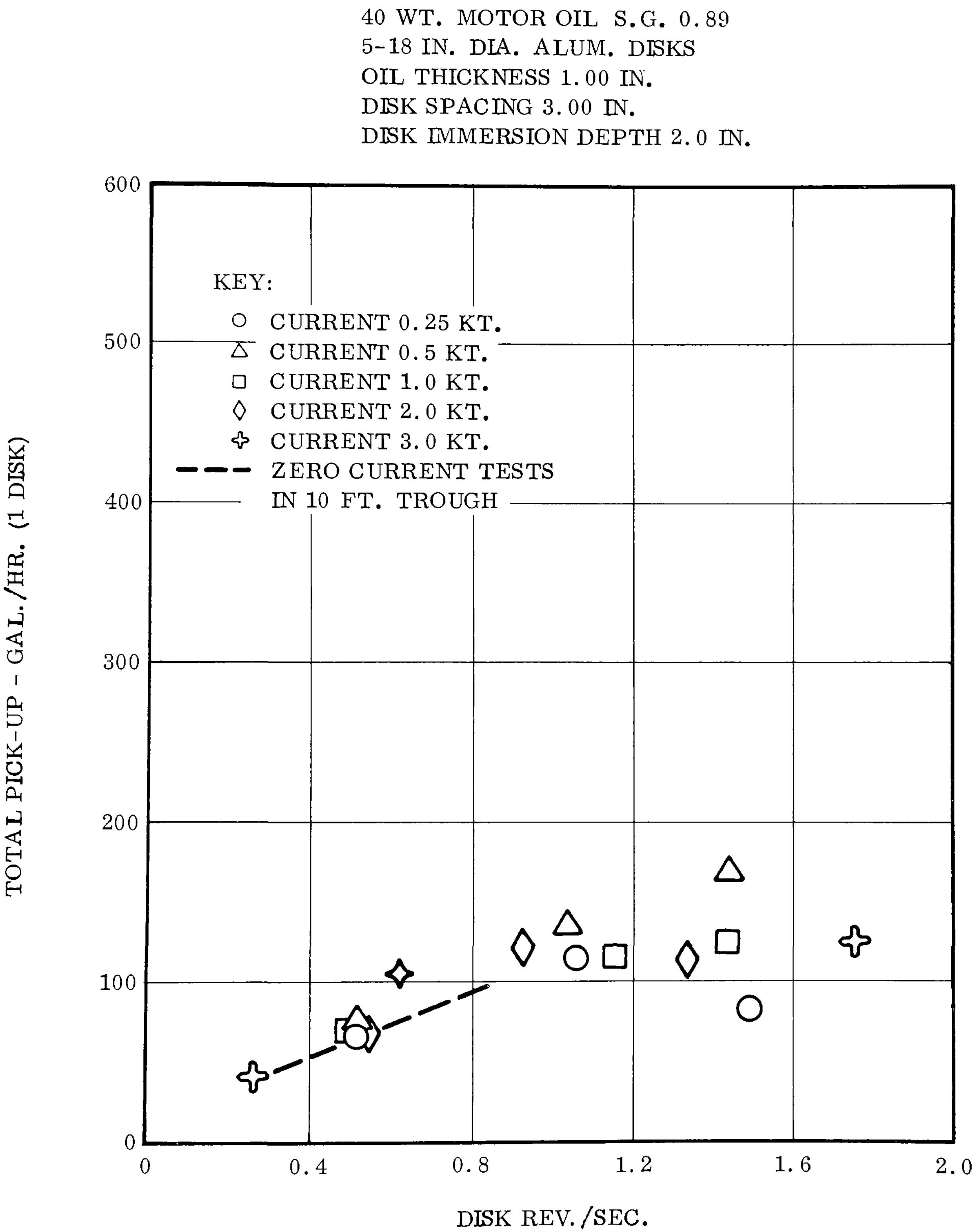


Figure 40. Oil Recovery Tests - Current Conditions

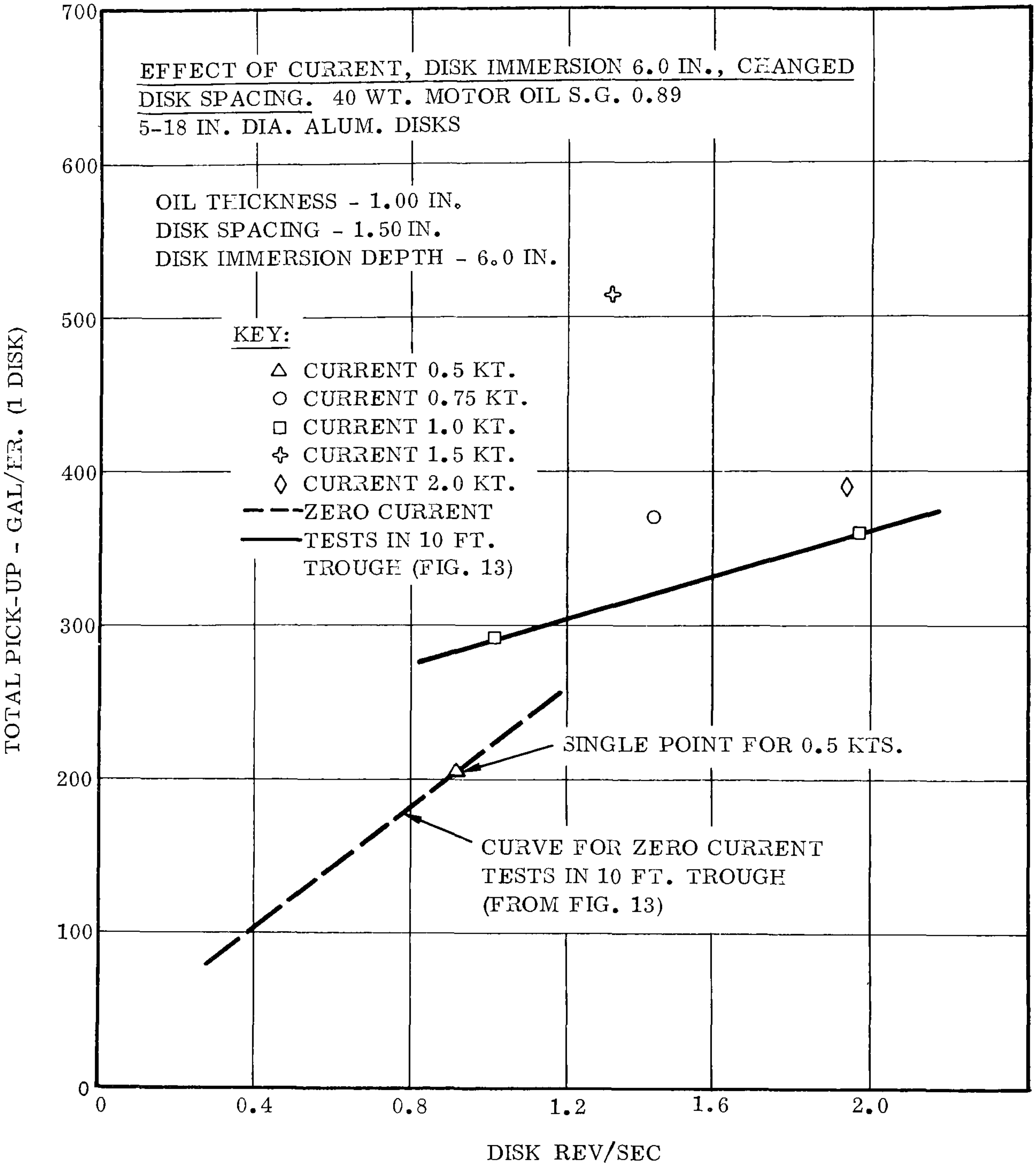


Figure 41. Oil Recovery Tests - Current Conditions

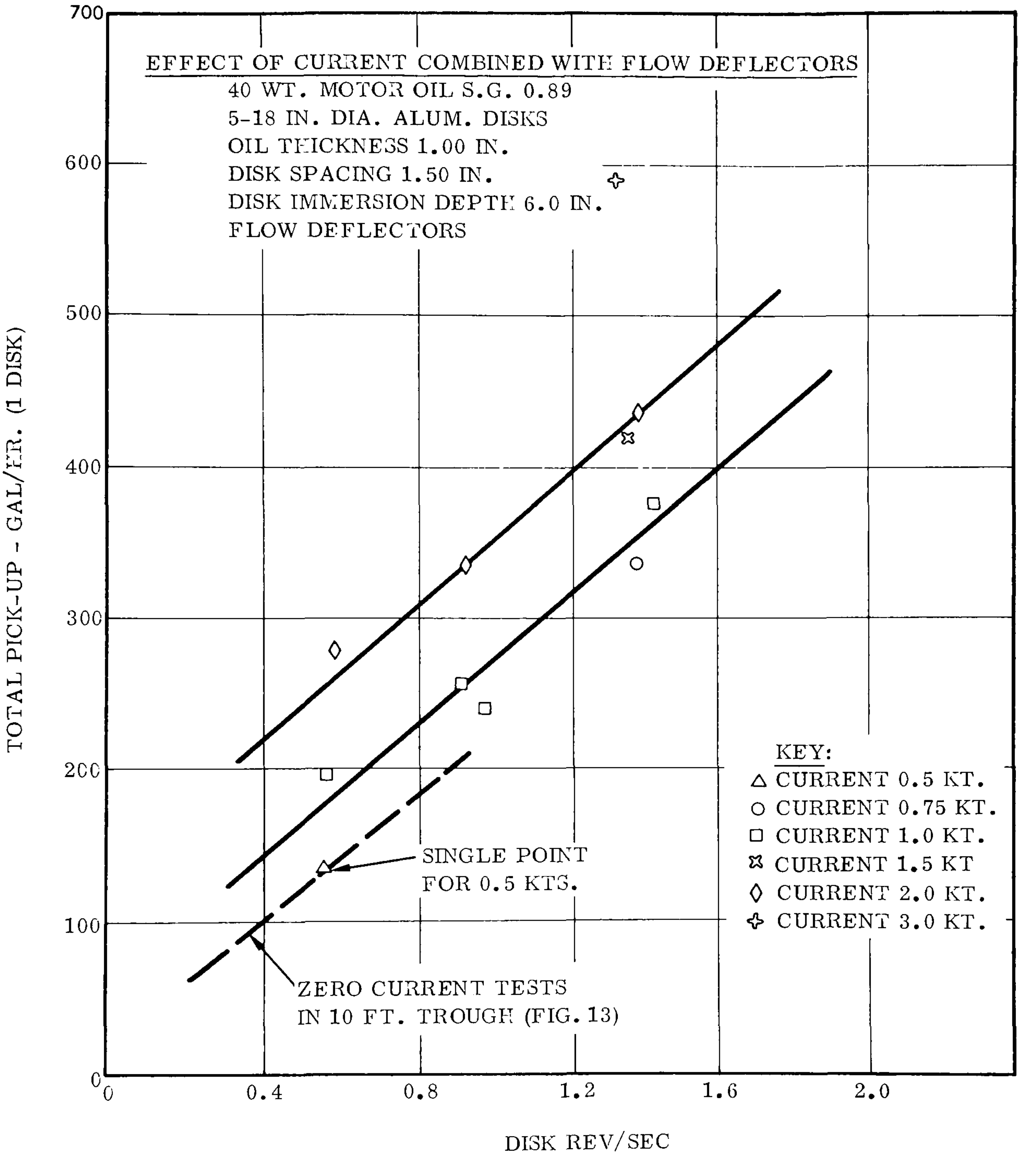


Figure 42. Oil Recovery Tests - Current Conditions

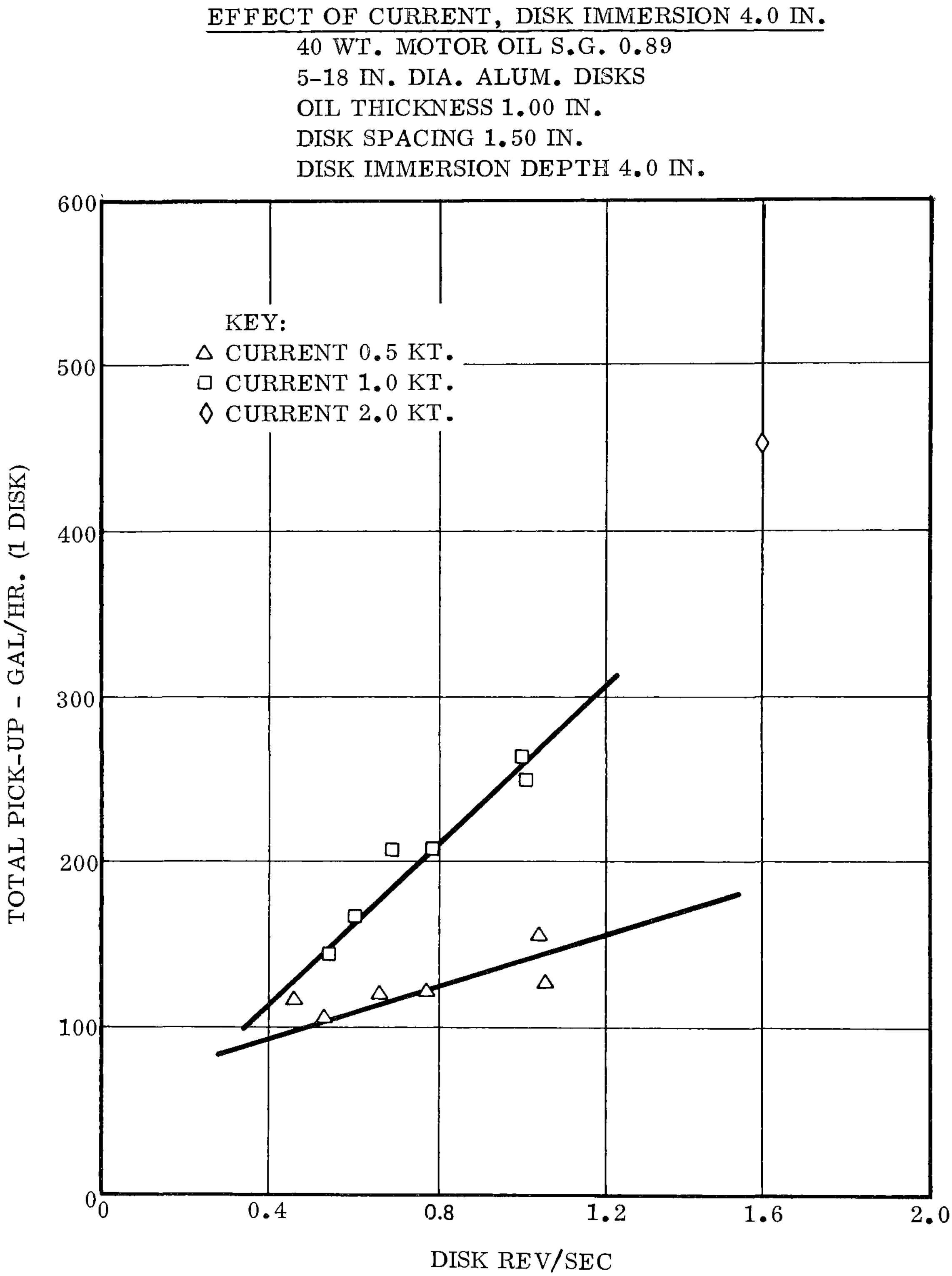


Figure 43. Oil Recovery Tests - Current Conditions

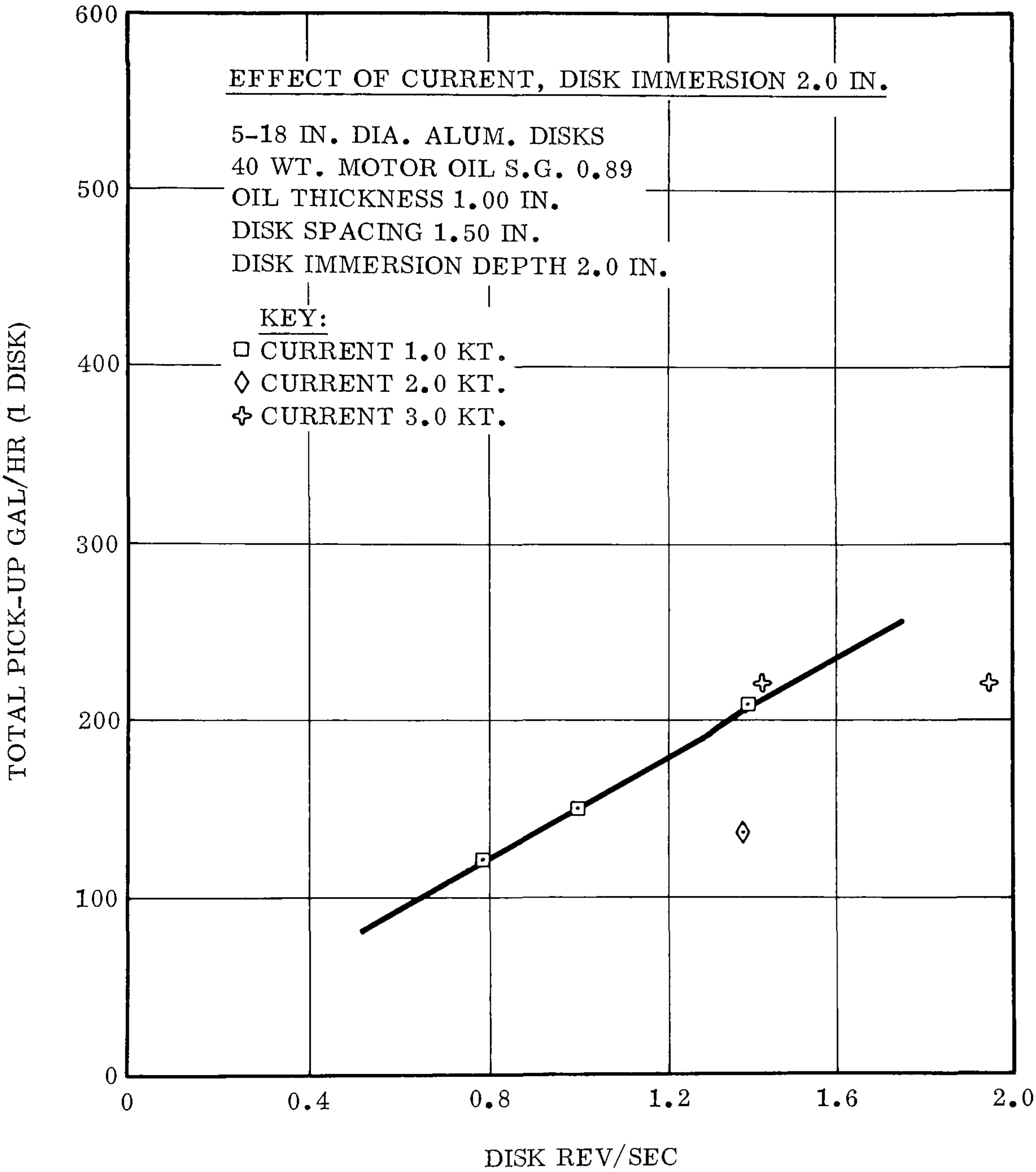


Figure 44. Oil Recovery Tests - Current Conditions

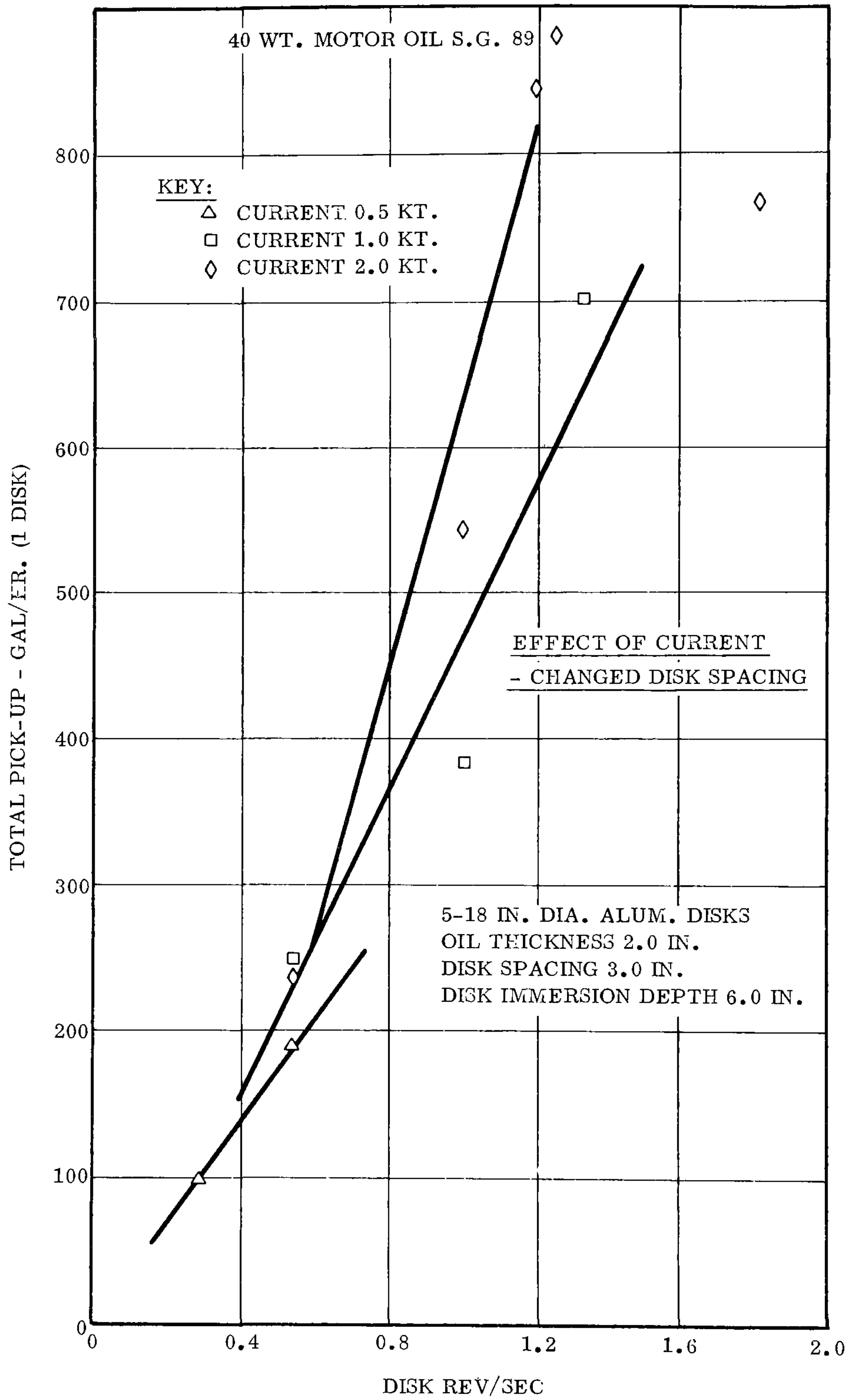


Figure 45. Oil Recovery Tests - Current Conditions

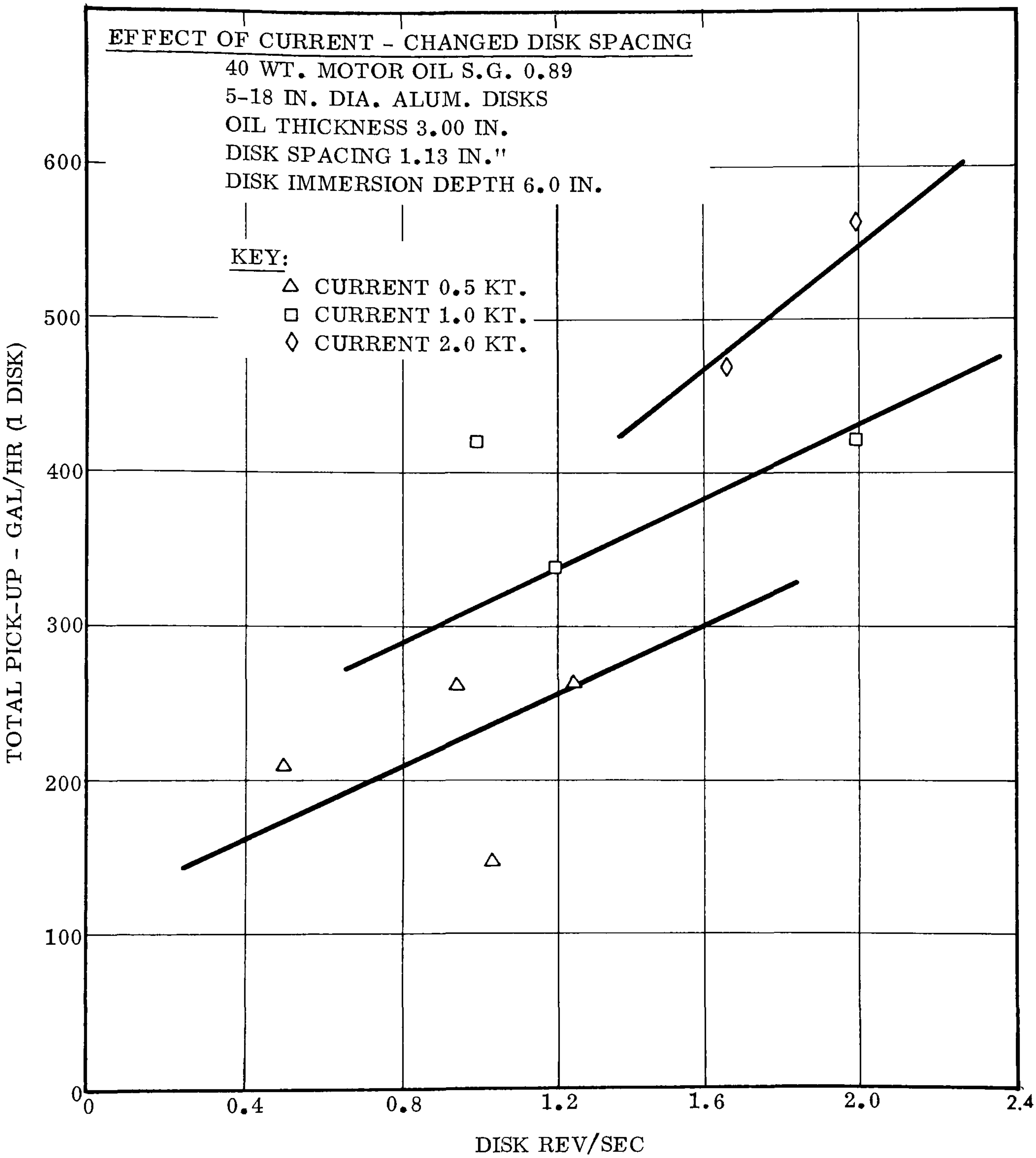


Figure 46. Oil Recovery Tests - Current Conditions

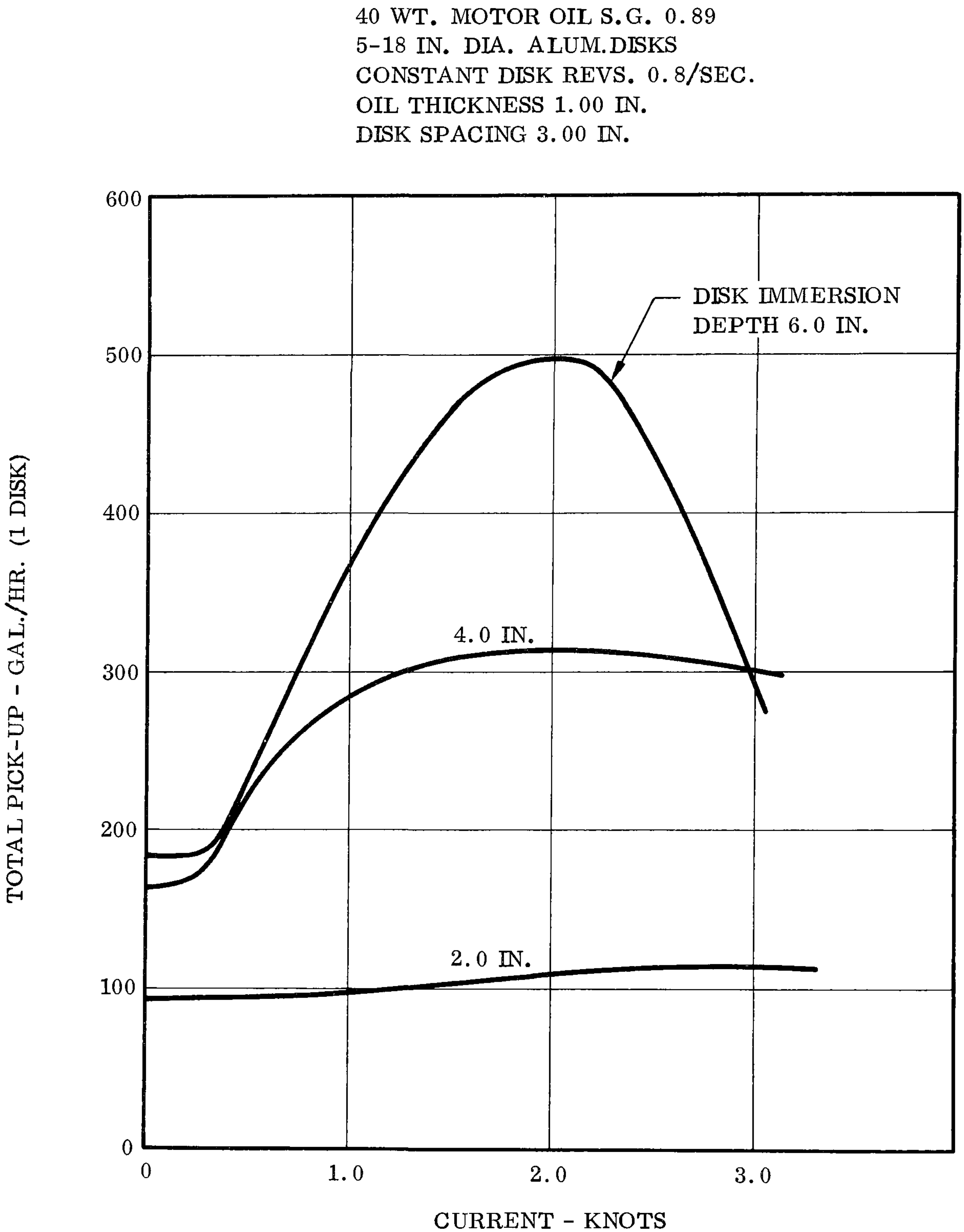


Figure 47. Oil Recovery Tests - Current Conditions

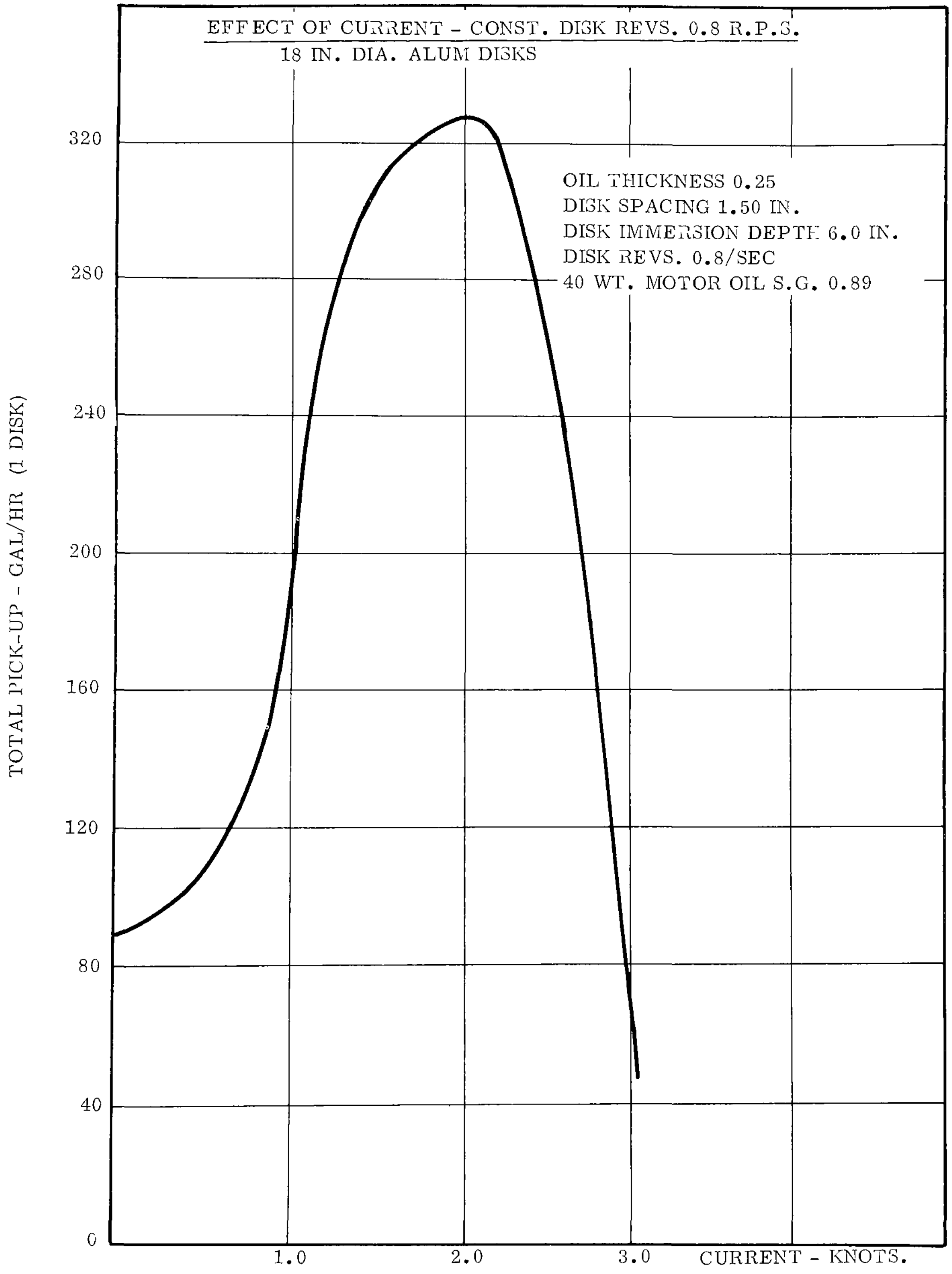


Figure 48. Oil Recovery Tests - Current Conditions

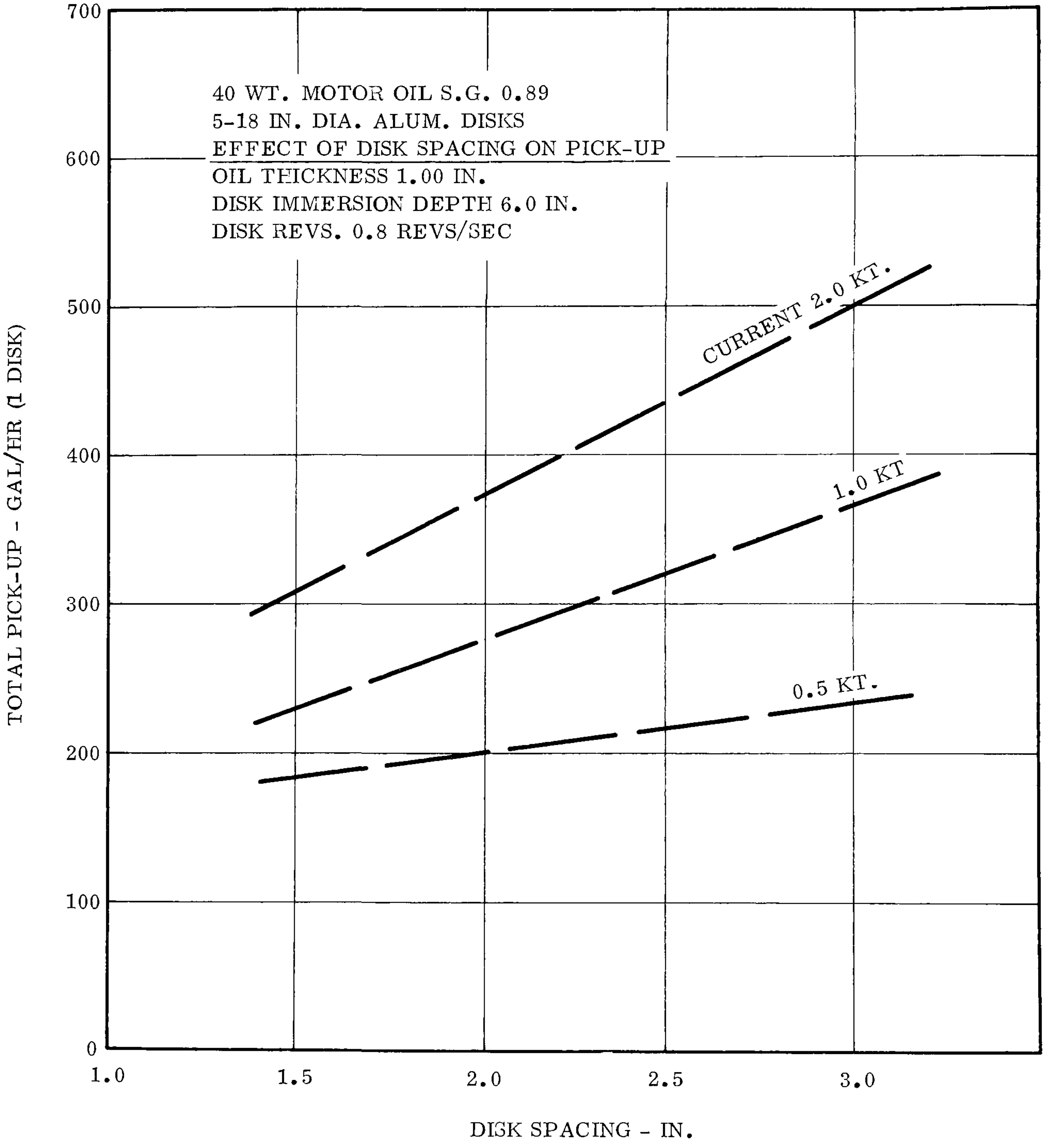


Figure 49. Oil Recovery Tests - Current Conditions

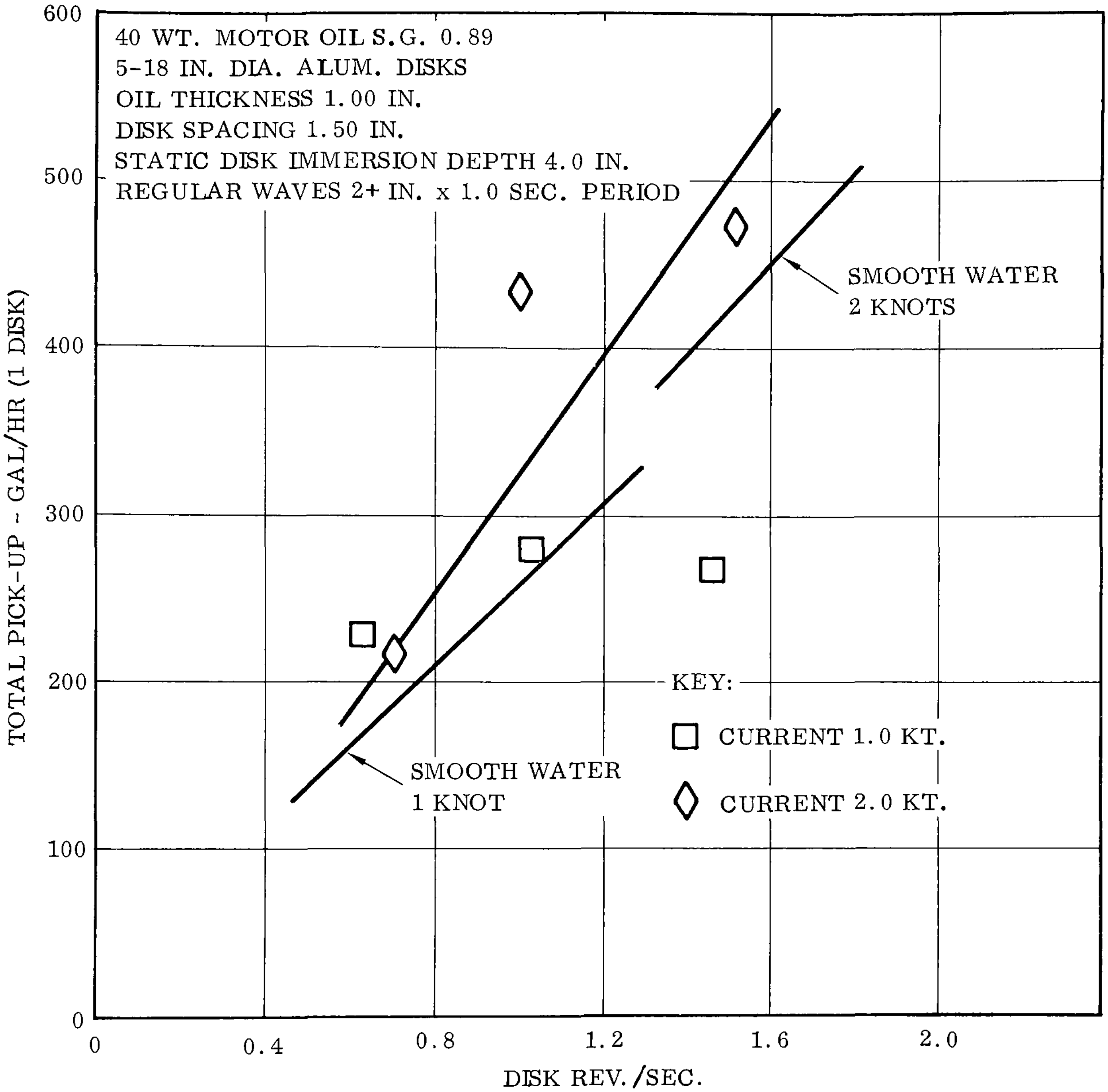


Figure 50. Oil Recovery Tests - Wave & Current Conditions

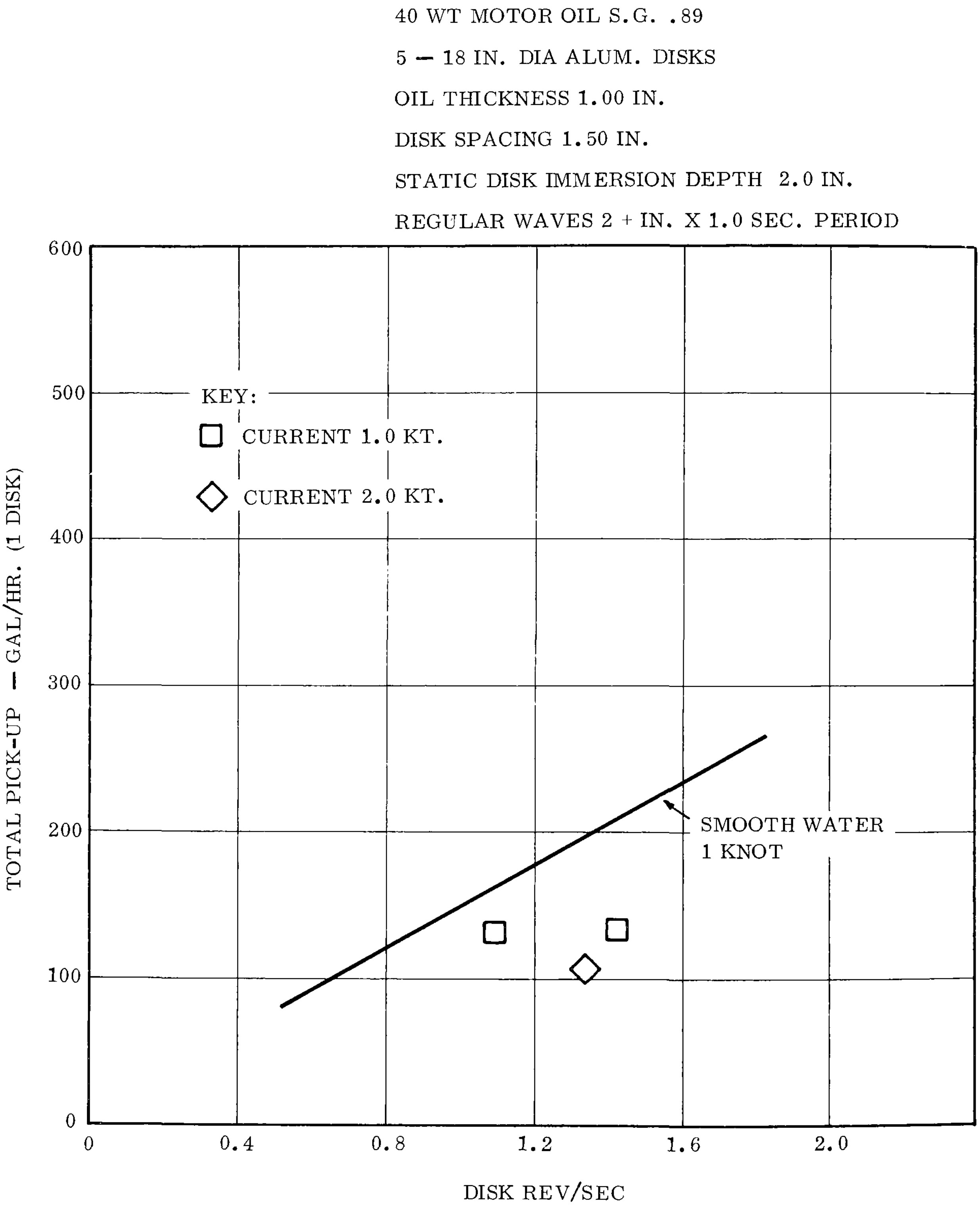


Figure 51. Oil Recovery Tests - Wave & Current Conditions

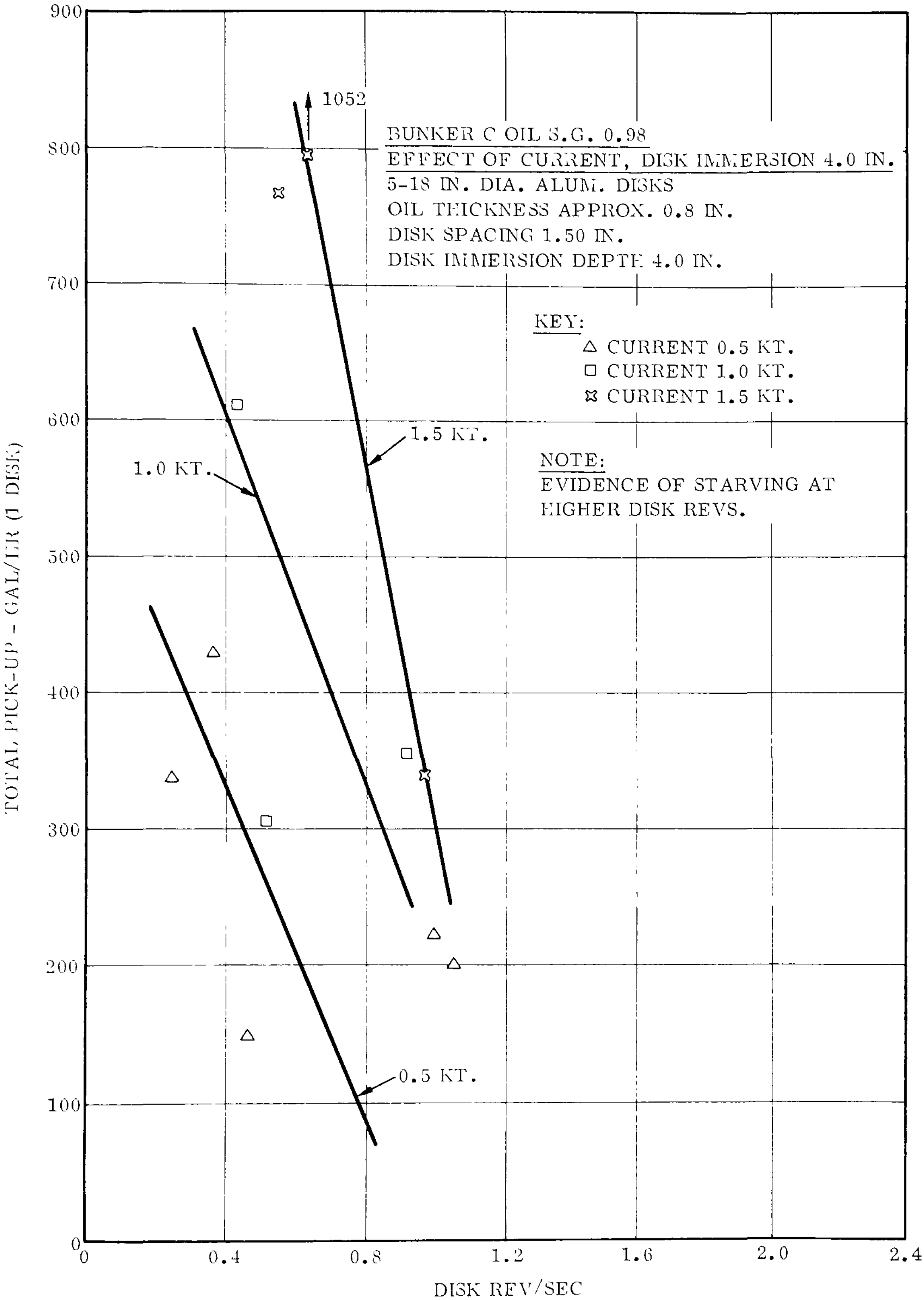


Figure 52. Oil Recovery Tests - Current Conditions

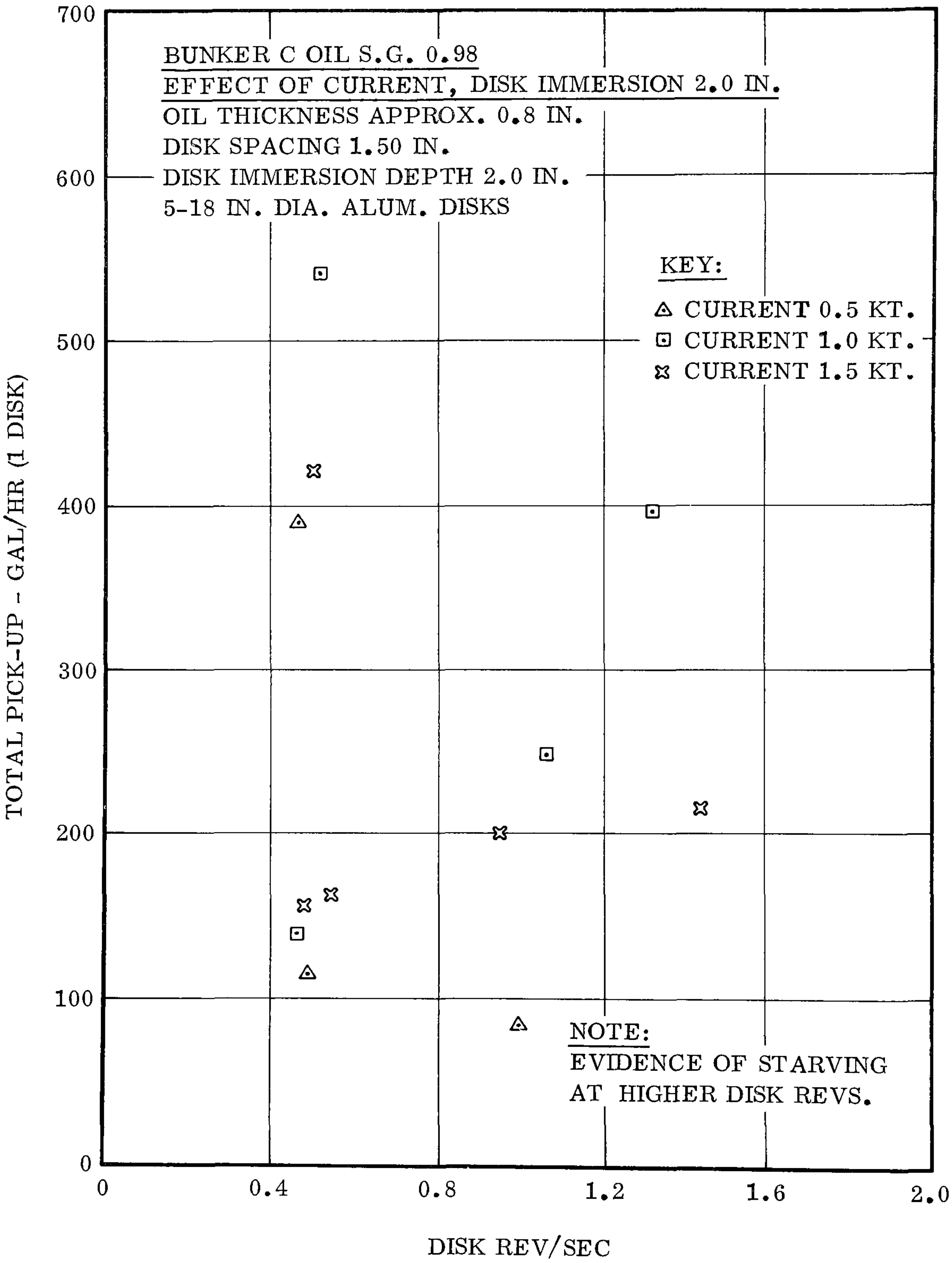


Figure 53. Oil Recovery Tests - Current Conditions

SECTION VIII

TECHNICAL DISCUSSION

STARVATION

Starvation of the disk is defined as a reduction of oil pick-up rate due to reduction of oil quantity adjacent to the disk. The fall off in oil quantity, which may become total, is due to insufficient oil feed to the disk to satisfy the oil pick-up rate. Factors affecting this are current, disk spacing, disk rotation rate, and oil properties, such as specific gravity, viscosity and surface tension.

The oil properties determine the oil spreading rate, which in turn affects the oil flow rate into the disk sides. Oil properties also affect the disk pick-up rate, and thus the demand for oil. Bunker 'C' oil, which has high viscosity and high specific gravity, has a very low spreading rate, but has a very high pick-up rate when the supply is maintained. Consequently it is very susceptible to starvation. Diesel oil, on the other hand, with its low viscosity and low specific gravity, has a very high spreading rate but low pick-up rate; it is much less liable to create a starvation condition.

In zero current conditions starvation manifests itself visually as a deep hollow in the undersurface of the oil surrounding the disk, so that in effect the disk is operating in an oil thickness which is much less than that of the oil 1/2 disk diameter away from the disk. This effect is compounded by adjacent disks which interfere with one another and prevent the oil flow from turning into the disk sides. It is expected that starvation can be minimized by proper design as follows:

1. Sufficient oil inflow to the disks either by material current flow, or by driving the disks system towards the oil.

2. Correct disk spacing.

3. Directing the oil into the disk sides by means of deflectors. This should be further investigated.

4. Correct disk rpm.

HERDING

For picking up Bunker 'C' or crude oil, both of which have a low spreading rate and tend to drift into an elongated slick under the influence of the prevailing winds and current, it is suggested that herding booms be attached to the bow of the barge in a V-shape.

Diesel oil, which has a very high spreading rate, rapidly becomes a thin slick with a thickness of only 1 or 2 millimeters. To pick up 50,000 gallons per hour with negligible water content it is necessary to contain the oil and build it up to a thickness of at least one-half inch. Fortunately diesel oil has low specific gravity and does not entrain with the water easily, so it should be possible to contain it with an anchored barrier system up to a current spread of 1 knot. The recovery barge would then have to operate within the barrier system.

Alternatively the powered disk recovery system could be part of the anchored barrier system, by putting the disks at the apex of the V-formation herding barriers.

SUPPORT PLATFORM AND STORAGE UNIT

A possible support platform and storage unit consisting of standard offshore barge was examined.

A pick-up rate of 50,000 gallons per hour equals 1190 barrels per hour. A tank barge 250 ft x 44 ft-6 in. has a capacity of 25,000 barrels of fuel oil. It could therefore operate with a powered disk system for 21 hours working as an independent unit.

A tank barge 320 ft x 55 ft-4 in. holds 56,000 barrels of fuel oil. It could operate with a powered disk system for 47 hours working as an independent unit. The above volumes of oil are of course reduced by water pick-up.

In order to maintain a relatively constant disk depth of immersion it would be desirable for the barge to have a natural frequency about 1/10 times the wave frequency. A 5 ft wave height is high Sea State 3 with a wave period of about 4.7 secs and a wave length of 100 ft. (The wave height is defined as the height of the highest 1/3 of the waves.) The wave frequency is 1/4.7 = 0.213 cycles/sec. Therefore the barge natural frequency should be 0.213 cycles/sec or a natural period of 47 secs. This is too drastic a requirement.

The relationship between ship speed, ship length, wave length, and natural period of oscillation is illustrated in Figure 54 of "Principles of Naval Architecture" by J. P. Comstock, (Ref. 2). Calculations are made using this graph.

Let us first assume a 100 ft length barge with a speed of 5 knots. $V/\sqrt{L} = 5/10 = 0.5$. Wave length divided by ship length = 1.0. If the wave length is equal to, or greater than the ship length, then we are in the zone of severe motions. This is the case here.

The period-length ratio $T/\sqrt{L}$ is 0.325

$$T = 0.325 \times 10$$

$$= 3.25 \text{ secs.}$$

The wave period is 4.7 secs.

Now assume a 250 ft length barge operating at a speed of 3 knots.

$$V/\sqrt{L} = 3/15.8 = \underline{0.19}$$

Wave length divided by ship length = 0.4.

From Ref. 2, the period-length ratio is 0.24.

$$T = 0.24 \times 15.8 = \underline{3.8 \text{ secs}}.$$

So it is obviously not possible to move away from the wave frequency by a factor of more than about 25 percent; however, Ref. 2 indicates that this is well into the zone of moderate motions and dry decks in irregular storm seas. A tank barge of 250 ft in length would be satisfactory both from the ship motions viewpoint, and for storage capacity.

EFFECT OF WIND

The effect of wind may be obtained from Reference 1, Page 3-11, which assumes a wind-induced surface current proportional to the wind velocity. The actual surface current will be between 2 and 3 percent of the winds velocity from basic oceanographic data. The results of Ref. 1 tests showed this constant to be slightly over 1 percent. It can conservatively be assumed that oil pick-up can be predicted in wind and current by adding 2.5 percent of the wind velocity to the current velocity. The difference between model results (1 percent) and the 2-3 percent observed in the ocean can be explained by the very short fetch in the test set up. From this, a 20 mph wind is equivalent to a 0.434 knot current. This would be added to the 2 knot design current to give 2.43 knots.

SECTION IX

THEORETICAL MODEL AND COMPARISON WITH EXPERIMENTAL RESULTS

THEORETICAL MODEL OF THE DISK SYSTEM

On the basis of the experimental data from tests conducted over wide ranges of the pertinent parameters involving oil properties, geometric and dynamic characteristics of the test apparatus, a theoretical model may be constructed which, when validated by comparison with the experiments, would allow one to design a full-scale system to operate under realistic oil slick conditions with predictable performance. In the following paragraphs such a theoretical model is developed, resulting in a set of generalized performance curves relating the pertinent parameters in terms of three dimensionless quantities which account for oil type, oil slick thickness, disk geometry, disk rotation rate and oil pumping rate. This model is then compared with the experimental results in the chapter following; and, finally, is used to develop a set of design criteria for a full-scale system.

Upon observing the oil pick-up mechanism of the rotating disk it can be readily concluded that the basic process is one of boundary-layer formation on a surface moving through a finite body of two viscous fluids. Because of the differences in properties of the two fluids - water and oil - it is possible, under appropriately controlled conditions, for the moving surface to form only an oil boundary layer. The object of establishing a theoretical model is to describe analytically the oil boundary-layer formation process in terms of the properties of the oil and the geometric and mechanical constraints of the oil recovery system. The general configuration to be analyzed is shown in Figure 54 below.

A disk of radius "R" is immersed to a depth of "D" in an oil slick of thickness "d." The chord at the immersion line is "C." The disk rotates at a rate "ω." The oil pick-up mechanism may be depicted as shown in Figure 55.

In this vertical section of the disk is shown the oil boundary-layer of thickness "δ," being pulled from the oil pool of thickness "d" up the disk at a vertical velocity of ωx, where x is the horizontal distance from the center of the disk to the point in question, as seen in Figure 55. The tangential velocity of the disk element at this point is ωr, and its vertical component is $\omega r \cos \theta = \omega x$.

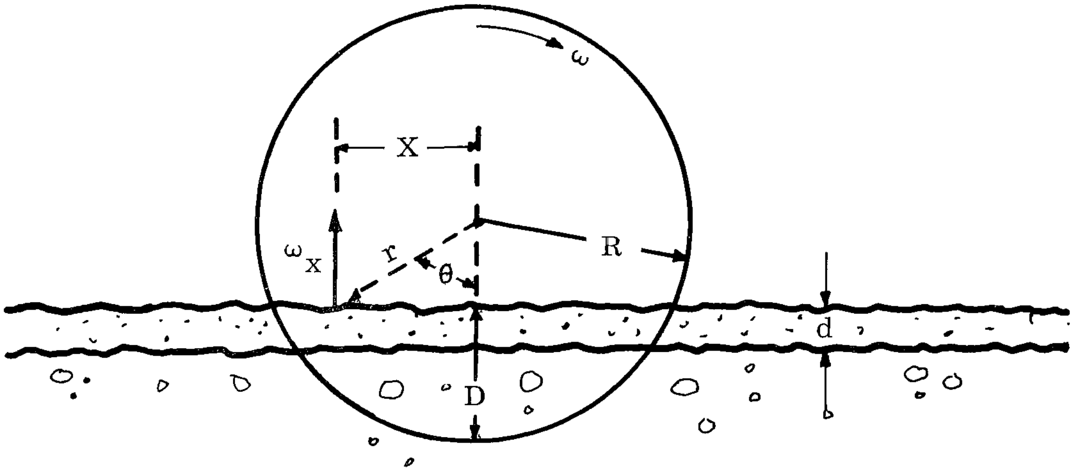


Figure 54. Disk Oil Recovery Configuration

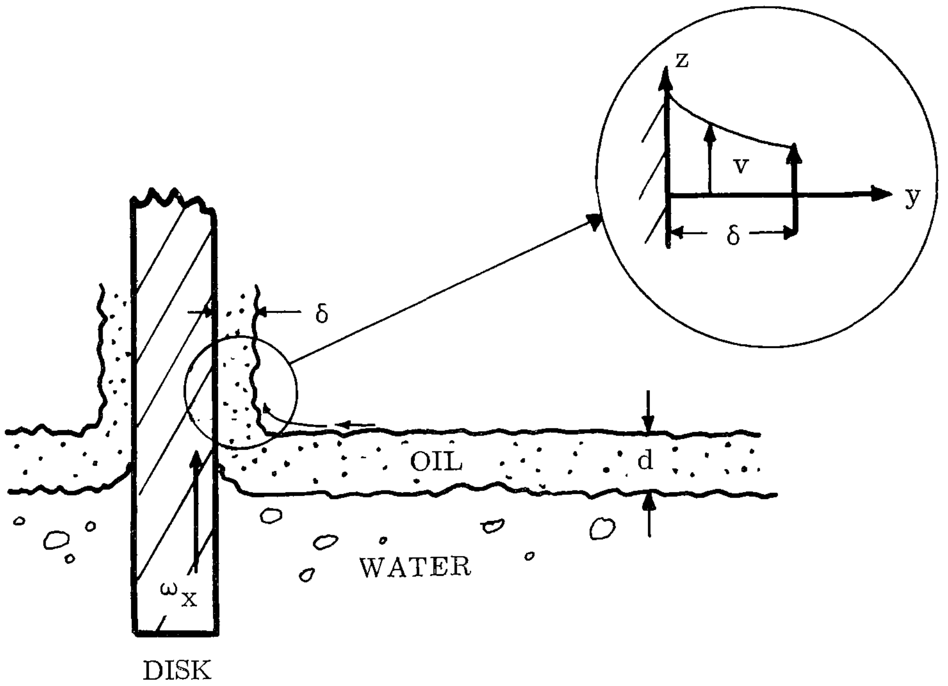


Figure 55. Oil Boundary-Layer Formation on Disk

Consider now the boundary-layer on the disk at the point where it just emerges from the slick, shown in the inset in Figure 55, where the velocity profile of this boundary-layer is depicted. The equation of motion of this layer may be developed by considering the equilibrium of forces acting on a differential element of thickness dy and height dz in the layer, as seen in Figure 56.

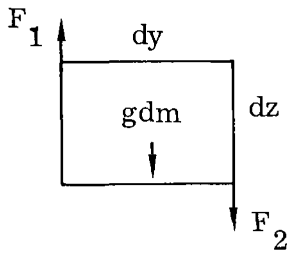


Figure 56. Equilibrium of Forces Acting on Boundary-Layer

The shearing forces F_1 and F_2 act on opposing faces of this volume element, and there is a body force gdm due to gravity. The equilibrium is expressed as

$$F_1 - F_2 - gdm = 0 \tag{1}$$

where the shearing force

$$F = -\mu \frac{dv}{dy} dx\ dz$$

and

$$dm = \rho\ dx\ dy\ dz$$

where dx is the depth in the x-direction.

The differential equation resulting from (1) is

$$\frac{d}{dy}\left(\mu \frac{dv}{dy}\right) = \frac{\rho g}{\mu} \tag{2}$$

Integration of Equation (2) yields

$$v = \frac{\rho g}{2\mu} y^2 + Ay + B \tag{3}$$

At the disk surface y = 0, and v = ωx, therefore the integration constant B in Equation (3) is

$$B = \omega x$$

At the edge of the boundary layer y = , so that

$$v_\delta = \frac{\rho g}{2\mu} \delta^2 + A\delta + \omega x \tag{4}$$

from which the constant of integration, A, can be expressed, in terms of v_δ and δ, as

$$A = \frac{1}{\delta} \left(v_\delta - \omega x - \frac{\rho g}{2\mu} \delta^2 \right) \tag{5}$$

Equation (3) now becomes

$$v = \frac{\rho g}{2\mu} y^2 + \frac{y}{\delta} \left(v_\delta - \omega x - \frac{\rho g}{2\mu} \delta^2 \right) + \omega x \tag{6}$$

It remains to determine δ and v_δ (the boundary-layer thickness and the velocity at the edge of the boundary-layer), which can be done by considering boundary conditions at the juncture of the horizontal oil slick surface and the vertical surface of the edge of the boundary-layer.

Figure 57 depicts the condition at this juncture where the shearing force at the edge of the boundary-layer is balanced by the surface tension of the slick surface.

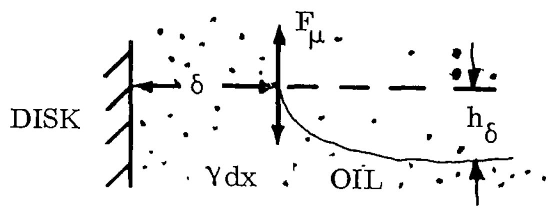


Figure 57. Boundary Conditions

$$F_\mu - \gamma\, dx = 0 \tag{7}$$

The shearing force F_μ is calculated from the velocity gradient at the edge of the boundary-layer, using Equation (6),

$$F_\mu = -\mu \left(\frac{dv}{dy}\right)_\delta h_\delta\, dx = -\mu \left(\frac{\rho g}{\mu}\,\delta + \frac{v_\delta - \omega x - \frac{\rho g\, \delta^2}{2\mu}}{\delta}\right) h_\delta\, dx$$

$$= -\left[\frac{\rho g \delta}{2} + \frac{\mu}{\delta}\left(v_\delta - \omega x\right)\right] h_\delta\, dx \tag{8}$$

Combining Equations (8) and (7) and rearranging, a quadratic equation in δ results:

$$\delta^2 + \frac{2\gamma}{\rho g h_\delta}\,\delta + \frac{2\mu}{\rho g}\left(v_\delta - \omega x\right) = 0 \tag{9}$$

from which a solution for δ in terms of h_δ is obtained.

$$\delta = \sqrt{\left(\frac{\gamma}{\rho g\, h_\delta}\right)^2 - \frac{2\mu}{\rho g}\left(v_\delta - \omega x\right)} - \frac{\gamma}{\rho g\, h_\delta} \tag{10}$$

The oil surface "fillet" height h_δ can be estimated from a balance of the surface tension and the gravity force, as shown in Figure 58.

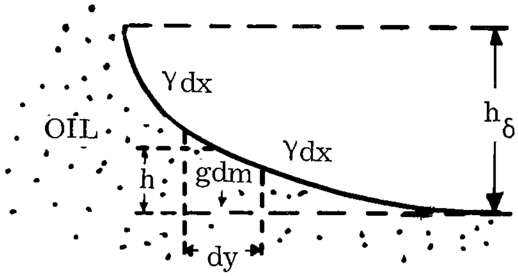


Figure 58. Oil Fillet

$$\gamma dx \left[\frac{\left(\frac{dh}{dy}\right)_2}{\sqrt{1 + \left(\frac{dh}{dy}\right)_2^2}} - \frac{\left(\frac{dh}{dy}\right)_1}{\sqrt{1 + \left(\frac{dh}{dy}\right)_1^2}} \right] - \rho gh \, dx \, dy = 0$$

The differential equation resulting from this force balance is

$$\frac{\rho gh}{\gamma} = \frac{d}{dy} \left[\frac{\frac{dh}{dy}}{\sqrt{1 + \left(\frac{dh}{dy}\right)^2}} \right] = -\frac{d}{dh} \left[\frac{1}{\sqrt{1 + \left(\frac{dh}{dy}\right)^2}} \right] \tag{11}$$

Integrating once yields

$$\frac{\rho gh^2}{2\gamma} = -\frac{1}{\sqrt{1 + \left(\frac{dh}{dy}\right)^2}} + C \tag{12}$$

Far from the disk, in the slick,

$$h = 0$$

and

$$\frac{dh}{dy} = 0$$

so that

$$C = 1$$

At the edge of the fillet next to the disk

$$h = h_\delta$$

and

$$\frac{dh}{dy} = - \infty$$

Therefore,

$$\frac{\rho g h_\delta^2}{2\gamma} = 1$$

or

$$h_\delta = \sqrt{\frac{2\gamma}{\rho g}} \qquad (13)$$

Substitution of (13) into (10) yields

$$\delta = \sqrt{\frac{\gamma}{2\rho g} + \frac{2\mu}{\rho g}\left(\omega x - v_\delta\right)} - \sqrt{\frac{\gamma}{2\rho g}}$$

This may be put into dimensionless form:

$$\bar{\delta} = \sqrt{1 + \frac{4\mu}{\gamma}\left(\omega x - v_{\delta}\right)} - 1 \qquad (14)$$

where

$$\bar{\delta} = \sqrt{\frac{2\,\rho g}{\gamma}}\,\delta \qquad (15)$$

Returning now to the determination of v_{δ}, it is seen that the continuity of flow from the slick up to the disk suggests that v_{δ}, on the average across the chord, is equal to the average lateral flow of the slick towards the disk. If Q is the volume of oil picked up by both sides of the disk per unit time, and if the length along the "water line" where oil is picked up is L, the preceding statement about continuity is

$$\frac{Q}{Ld} = v_{\delta} \qquad (16)$$

Noting in Equation (14) that the boundary-layer thickness is zero at a finite distance $x = x_{\delta}$ from the disk center-line, then

$$\omega x_{\delta} = v_{\delta} = \frac{Q}{Ld}$$

and

$$L = 2\left(\frac{C}{2} - x_{\delta}\right)$$

so that

$$\omega x_{\delta} = \frac{Q}{2\left(\frac{C}{2} - x_{\delta}\right) d} \qquad (17)$$

and

$$v_\delta = \frac{2Q}{Cd} \frac{1}{1 + \sqrt{1 - \frac{8Q}{\omega C^2 d}}} \tag{18}$$

Equations (18) and (14) may be substituted into Equation (6) to yield an equation for the velocity profile in the oil boundar-layer in terms of the total oil pick-up rate.

The pick-up rate per unit width along the chord is

$$\frac{dQ}{dx} = \int_0^\delta vdy = \int_0^\delta \left[\frac{\rho g}{2\mu} y^2 + \frac{y}{\delta}\left(v_\delta - \omega x - \frac{\rho g}{2\mu}\delta^2\right) + \omega x\right] dy$$

$$= \frac{\delta}{2}\left(\omega x + v_\delta - \frac{\rho g}{6\mu}\delta^2\right) \tag{19}$$

The total rate of pumping for both sides of the disk along the chord from x_δ to C/2 is then

$$Q = 2\int_{x_\delta}^{C/2}\left(\frac{dQ}{dx}\right) dx = \int_{x_\delta}^{C/2} \delta \left(\omega x + v_\delta - \frac{\rho g}{6\mu}\delta^2\right) dx \tag{20}$$

This equation is made dimensionless by multiplying by $\omega\sqrt{\frac{2\rho g}{\gamma}}\left(4\frac{\mu}{\gamma}\right)^2$:

$$\omega Q\sqrt{\frac{2\rho g}{\gamma}}\left(4\frac{\mu}{\gamma}\right)^2 = \int_x^{C/2}\sqrt{\frac{2\rho g}{\gamma}}\,\delta\left[\frac{4\mu}{\gamma}(\omega x - v_\delta) + \frac{8\mu}{\gamma}v_\delta - \frac{1}{3}\left(\frac{2\rho g}{\gamma}\delta^2\right)\right] d\left(\frac{4\mu}{\gamma}\omega x\right) \tag{21}$$

With a change of variables

$$\xi = \frac{4\mu}{\gamma}(\omega x - v_\delta) \tag{22}$$

Equation (20) becomes

$$\omega Q \sqrt{\frac{2\rho g}{\gamma}} \left(\frac{4\mu}{\gamma}\right)^2 = \int_0^{\xi_{max}} \bar{\delta} \left(\xi + \frac{8\mu}{\gamma} v_\delta - \frac{1}{3} \bar{\delta}^2\right) d\xi \qquad (23)$$

in which

$$\xi_{max} = \frac{4\mu}{\gamma} \left(\omega \frac{C}{2} - v_\delta\right) \qquad (24)$$

and

$$\sqrt{\frac{2\rho g}{\gamma}}\, \delta = \bar{\delta} = \sqrt{1 + \xi} - 1 \qquad (25)$$

by Equation (14).

Integration of Equation (23) yields

$$\omega Q \sqrt{\frac{2\rho g}{\gamma}} \left(\frac{4\mu}{\gamma}\right)^2 = \frac{4}{3} \left\{ \frac{4\mu}{\gamma} v_\delta \left[(\xi_{max} + 1)^{3/2} - \frac{3}{2} \xi_{max} - 1 \right] + \frac{1}{5} \left[(\xi_{max} + 1)^{3/2} (\xi_{max} - 4) + 5\, \xi_{max} + 4 \right] \right\} \qquad (26)$$

From (24)

$$\frac{4\mu}{\gamma} v_\delta = \frac{2\mu}{\gamma} \omega C - \xi_{max} \qquad (27)$$

and from (18) and (27) it can be shown that

$$\omega Q \left(\frac{4\mu}{\gamma}\right) = \left(\omega C \quad \frac{\gamma\,\xi_{max}}{2\mu}\right) \xi_{max}\, d \tag{28}$$

Substitution of (27) and (28) into (26) results in an expression for ωC in terms of ξ_{max}:

$$\frac{\mu}{\gamma}\,\omega C = \frac{1}{2}\,\xi_{max} + \frac{1}{10}\,\frac{5\,\xi_{max} + 4 + (\xi_{max} - 4)\,(\xi_{max} + 1)^{3/2}}{\frac{3}{2}\,\xi_{max}\left(\sqrt{\frac{2\rho g}{\gamma}}\,d + 1\right) - (\xi_{max} + 1)^{3/2} + 1} \tag{29}$$

Equation (28) can be re-written as

$$\frac{\mu}{\gamma}\sqrt{\frac{\rho g}{\gamma}}\,\frac{Q}{C} = \frac{\xi_{max}}{4}\left(\sqrt{\frac{\rho g}{\gamma}}\,d\right)\left(1 - \frac{\xi_{max}}{\frac{2\mu}{\gamma}\,\omega C}\right) \tag{30}$$

Equations (29) and (30) are thus two parametric equations in ξ_{max} for the disk rotation rate and the disk oil pumping rate. By choosing suitable values of ξ_{max}, for any given values of the oil properties and disk geometry, the dimensionless pumping rate $Q \equiv \mu/\gamma \sqrt{\rho g/\gamma}\; Q/C$ can be plotted against the dimensionless rotation rate $\omega \equiv \mu/\gamma\,\omega C$, as has been done in Figure 59. Three curves are shown, for values of the dimensionless slick thickness $d \equiv \sqrt{\rho g/\gamma}\; d$ from 0.1 to ∞ (very thick slick).

In order to gain better physical feeling for this universal pumping rate equation, it would be useful to tabulate the actual values of the physical constant associated with the three types of oils studied in the experimental program, as well as some examples of typical numbers resulting from representative values of the physical and geometric parameters.

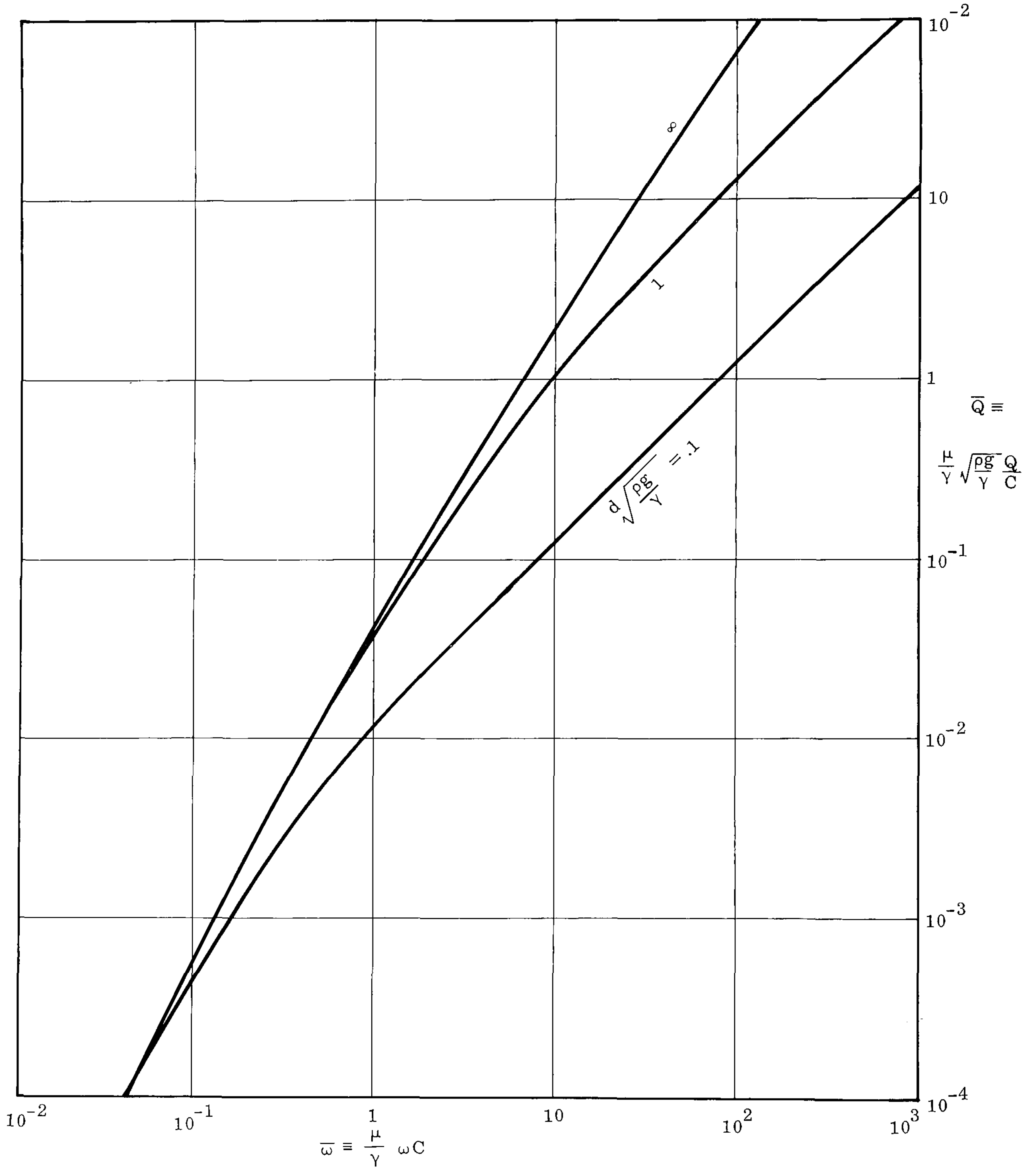


Figure 59. Theoretical Model Results

		Diesel	40 weight	Bunker C	
Surface Tension	γ	28.5	30.0	34.6	dynes cm^{-1}
Viscosity	μ	4.2×10^{-2}	5.0	50.6	gm cm^{-1} sec^{-1}
Density	ρ	0.842	0.895	0.979	gm cm^{-3}
	μ/γ	1.48×10^{-3}	1.67×10^{-1}	1.47	cm^{-1} sec
	$\sqrt{\frac{\rho g}{\gamma}}$	5.38	5.41	5.27	cm^{-1}

It is seen that the quantity μ/γ has the dimension of $(\text{velocity})^{-1}$ and that $\sqrt{\rho g/\gamma}$ has the dimension of $(\text{length})^{-1}$, so that they are used in non-dimensionalizing the pumping rate, the rotation rate and the slick thickness.

Same sample calculations follow:

	Diesel	40-weight	Bunker C	
Disk Immersion Chord C	100	100	100	cm
Slick Thickness d	1.0	1.0	1.0	cm
Dimensionless Thickness $\bar{d}$	5.38	5.41	5.27	
Rotation Rate ω	1.0	1.0	1.0	rad sec^{-1}
Dimensionless Rotation Rate $\bar{\omega}$	0.148	16.7	147	
Dimensionless Pumping Rate				
$\bar{Q}$ (from Figure)	1.2×10^{-3}	2.5	60	
Pumping Rate (per disk) Q	15	277	775	cm^3 sec^{-1}
	14	263	737	gal hr^{-1}

It can be seen from these values of the pumping rate that the major effect, as would be expected, comes from the viscosity of the oil, the lower viscosity of the diesel oil causing a thinner boundary-layer on the disk and thereby a lower pumping rate, for the same disk geometry and rotation rate as used for a more viscous oil. One could, however, suggest that the rotation rate be increased in order to pump more diesel oil. The theory, in fact, does not impose any limit on $\bar{\omega}$ and, thereby, on $\bar{Q}$. A practical limit, however, may be expected to prevail, from a consideration of the fact that the disk, being partially immersed also in water, would also pick up water, whereas the theory as formulated here, does not take this into account. The test results do indicate this limit for water-free oil pick-up exists for each of the three oils tested.

COMPARISON OF THEORY WITH EXPERIMENT

Before proceeding with a comparison of the theory with data gathered from the experimental program it may be well to recall the assumptions and limitations under which the theoretical model is constructed. The theory essentially accounts for the vertical lifting of oil from a slick by the viscous shearing action of a vertically moving surface. Implicit in this formulation is the assumption that there is a constant reservoir of oil with a uniform and constant thickness, and that the oil surface is smooth. It is further assumed that the moving surface preferentially picks up oil rather than water. Thus the limited scope of the theory does not take into account, except as a boundary condition where the oil flow turns from horizontal to vertical, the "feeding" of the disk by the lateral approach of the bulk of the oil slick. Conceivably the oil slick, without external stimulus, may not flow fast enough under the actions of gravity, viscosity and surface tension, to sustain the pumping action of the disk, in which case the assumption of a constant slick thickness approaching the disk would be violated, and the disk "starves." The constant reservoir assumption of the theory can practically be met by moving the oil slick past the disk so that the latter is always operating in a fresh pool of oil. The question of water pick-up is disposed of basically by assuming that the disk surface does not "wet" water while it does wet oil. Any actual departure from this perfect non-wetting assumption must be established experimentally, as will be discussed in this section. The effects of a wavy oil slick surface are beyond the scope of the analysis, and can only, at this stage in the development of the theoretical model, be assessed experimentally. It may, however, be suggested that the effects of waves can no doubt be reduced if the displacement of the oil surface does not result in significant variations in the immersion depth of the disk.

For a gross assessment of the validity of the theory one may refer to Figure 60, which shows all the data points from the static tests (no current) and to Figure 61, which shows all the data points from the towed tests. It is seen that the great majority of the data points fall within the region in the $\bar{Q} \sim \bar{\omega}$ plane bounded by the theoretical performance lines for an infinitely thick slick and for a thin slick of dimensionless thickness $\bar{d} = 0.1$ (which corresponds to a physical thickness of about 0.02 cm for all three oils tested). The intermediate theoretical curve for $\bar{d} = 1$ corresponds to a physical thickness of about d = 0.2 cm, so that most of the tests would be expected to fall above this curve. For the static tests, Figure 60, the un-flagged data points (for tests with no water pick-up) for diesel oil mostly fall about the theoretical curve. For the 40-weight oil the un-flagged data points fall predominantly between the theoretical curves for $\bar{d} = 1$ and $d = \infty$. The fairly large number of flagged points, which lie below the line for d = 1 suggests that the "effective" slick thickness at the disk is less than the actual (far away from the disk) because of "starvation" - or lack of proper "priming" of the pump. This effect is more pronounced when one examines the data from the Bunker C oil tests, wherein very few data points are un-flagged (without water pick-up). The starvation effect, which is an effective thinning of the slick near the disk, presumably also promotes water pick-up, especially if there are actual breaks in the slick surface due to the pumping action of the disk.

The starvation effects are apparently considerably lessened when there is current carrying the oil towards the disks, as is evident in Figure 61, in which tow-basic test data for 40-weight and Bunker C oils are shown. Two facts are significant, on comparing Figure 60 with Figure 61. One is the general shifting upward along the theoretical curves of the test points; the other is the reduced number of flagged data points relative to the unflagged ones. These two observations suggest that the primary effect of current is to enhance the priming of the disks so that they can operate to higher rotational rates than in the static case before water entrainment sets in.

To see how much effect current has on a portion of Figure 61 is enlarged and shown in Figure 62 with data chosen for different current values but with a constant slick thickness, corresponding to $\bar{d} = 14$. It is seen that the groups of data points move up with increasing current, such that they approach the theoretical curve for $\bar{d} = 14$ as current increases from 0.25 knot to 2.0 knots. There is a reversal of this trend as the current increases to 3.0 knots, however. The reason for such a maximum in current for maximum water-free pumping is probably that at high currents the slick is pulled away from the disks, rather than being herded towards the disks at some low but not zero value of the current.

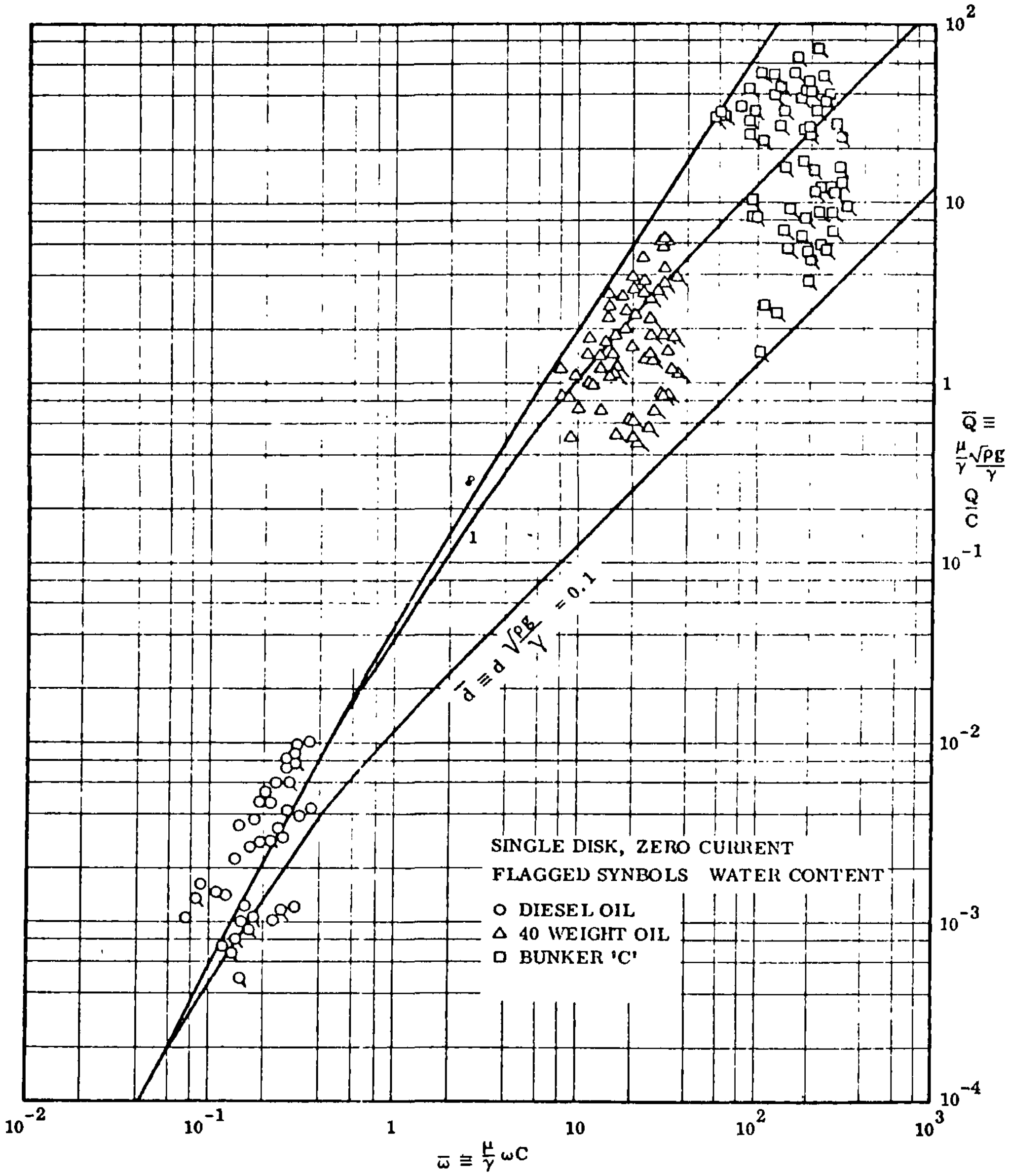


Figure 60. Comparison of Theory with Experiment - No Current

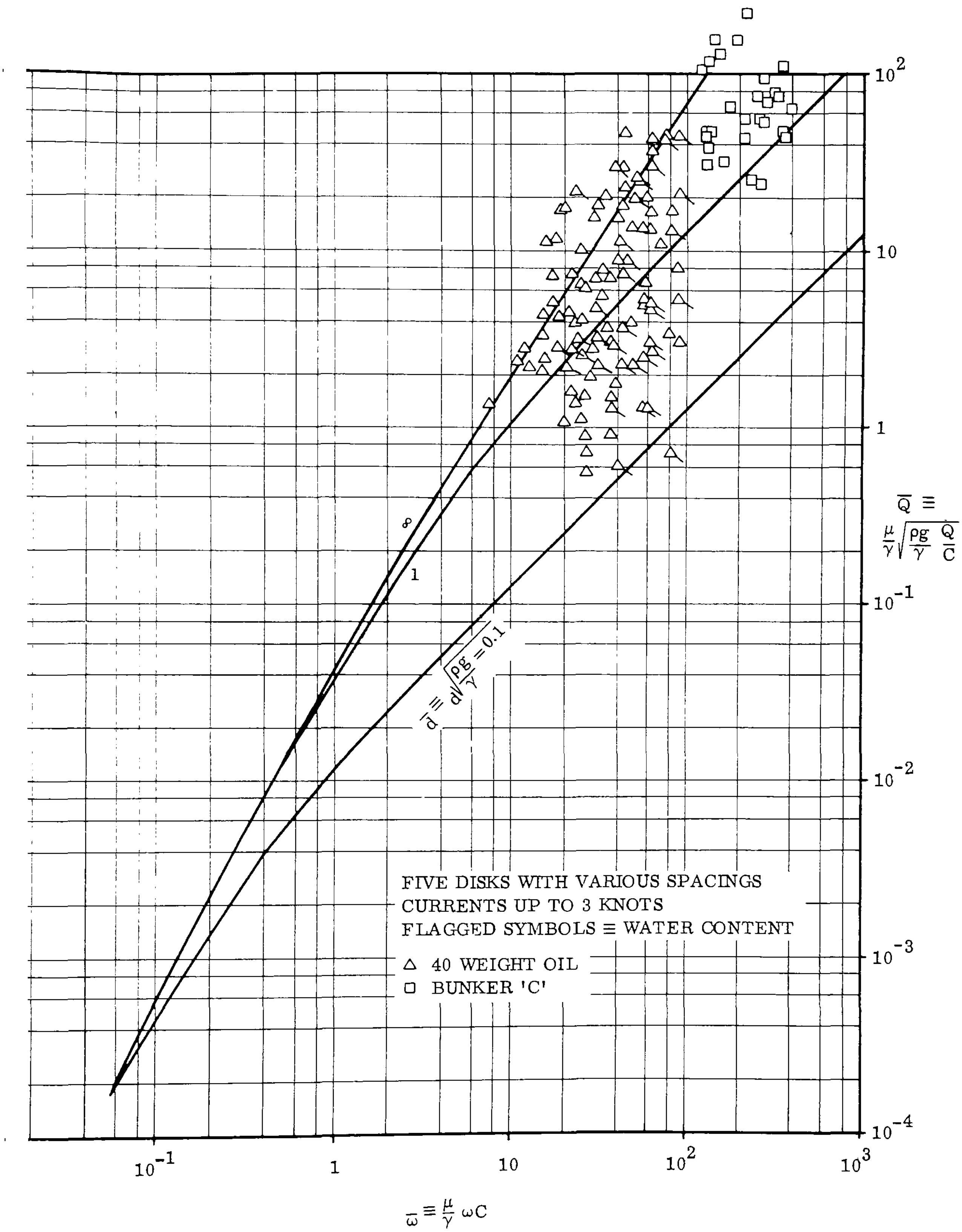


Figure 61. Comparison of Theory with Experiment - With Current

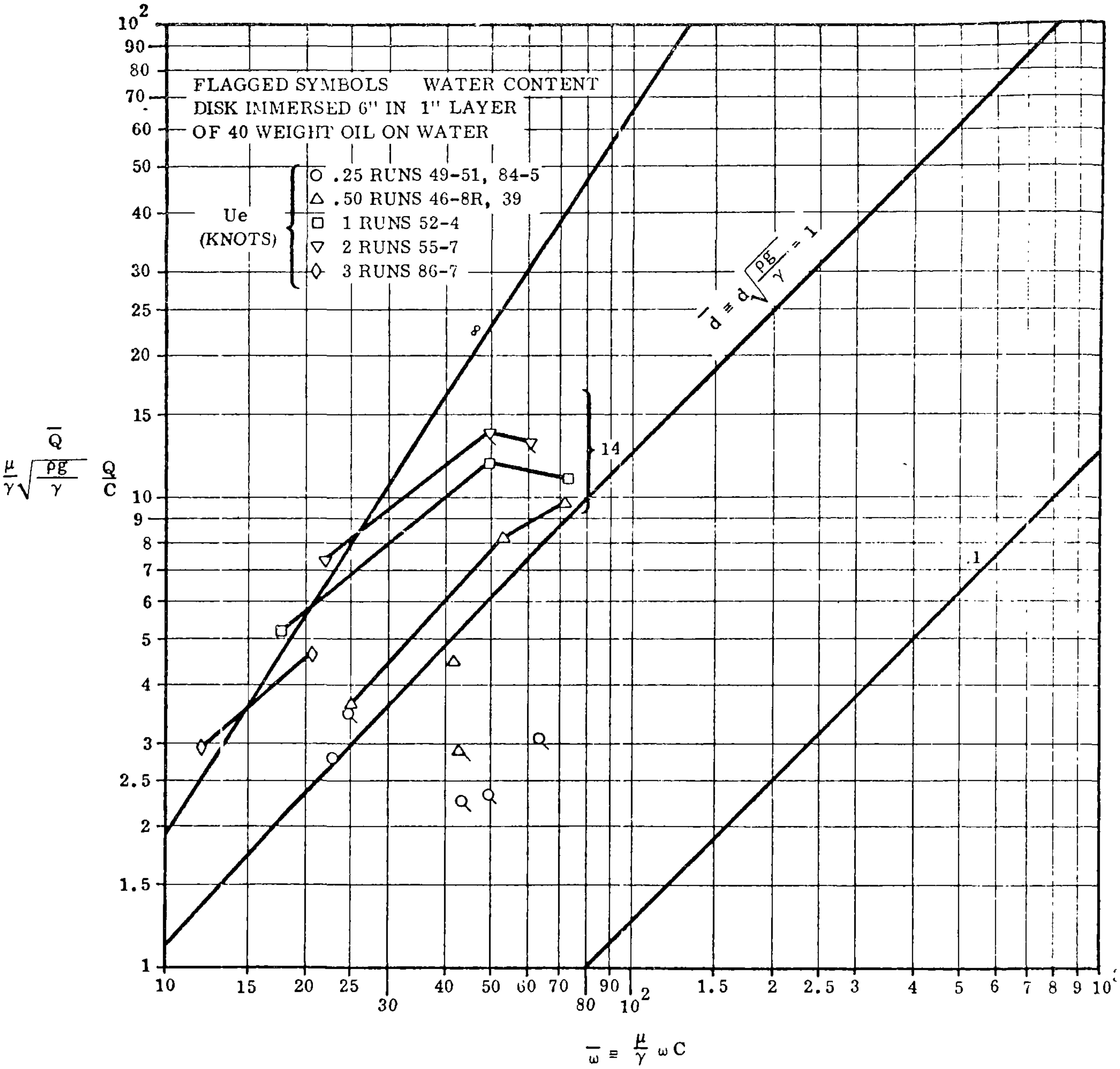


Figure 62. Effect of Current on Collection at Constant Slick Thickness

The agreement with theory at an optimum current for a relatively thin slick can also be seen in the data shown in Figure 63. This is the case for d = 3.4 (d = 0.25 inch). At a low current of 0.5 knot the test data fall considerably below the theoretical curve for d = 3.4. But as the current increases to 2 knots the test points come quite close to the theoretical values. Again, as the current increases past 2 knots, the pumping rate falls back down and water entrainment sets in.

Short of a complete analysis of the flow field in the oil approaching the disks, it will not be possible to give a good accounting for the limiting disk rotation rate at which water entrainment sets in. The level of effort planned for the present investigation does not permit such a broadened scope of the theoretical work; so that for the time being one would have to resort to empirically determined limits to the disk rate for design purposes. An overall examination of the data in Figure 61 indicates that a limiting value of the dimensionless rotation rate w = 60 should be appropriate for the 40-weight oil, and that w = 100 should result in water-free pick-up of Bunker-C oil. Since no tow-basin tests were run with Diesel oil it will be necessary to estimate a limiting for it by inference from the data for the heavier oils. Comparison of data for 40-weight and Bunker-C in Figures 60 and 61 show that there is an increase by a factor of about 2 to 3 in the pumping rate when currentprevails. On this basis a limiting disk rotation rate of $\bar{\omega} = 1$ is assigned to diesel oil.

Once a limiting (maximum) is established the maximum pumping ability of a given disk is set. The total pumping rate that can be achieved by a system of disks depends then only on the number of disks employed. For compactness one would want these to be placed as closely as possible along a common shaft. These must, however, exist a lower limit to the spacing between disks beyond which adjacent disk surfaces would interfere with each other, with consequent loss of pumping performance. An estimate of this minimum is made below.

The spacing between disks would be large enough to prevent the oil from filling the space and reducing the pumping effectiveness of the disks. The minimum spacing would be given by the widths of the oil layers on the disk surfaces plus the width of the oil fillet between these layers. The width of the oil layers is

$$2\,\delta_{max} = \sqrt{\frac{2\gamma}{\rho g}}\left[\sqrt{1+\xi_{max}}\;-1\right]$$

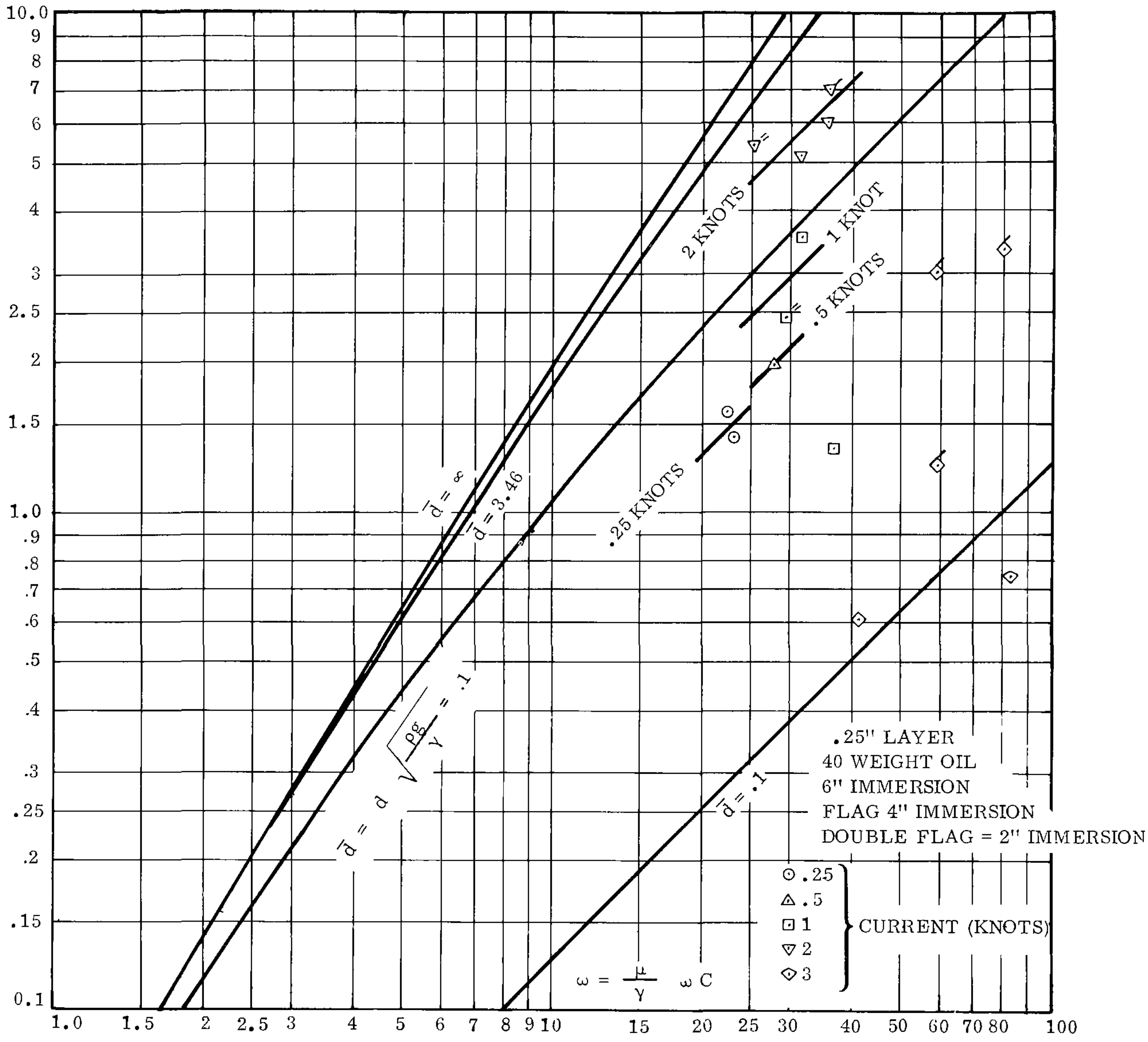


Figure 63. Effect of Current on Collection at Constant Slick Thickness - Thin Slick

and the width of the fillet is not more than $2\gamma/\rho g h_{min} = y_1$ (see Figure 64), where h_{min} is the height of the fillet trough. For $y_1 = 18\, h_{min}$

$$h_{min}^2 = \frac{1}{9}\left(\frac{\gamma}{\rho g}\right)$$

or

$$h_{min} = \frac{1}{3}\sqrt{\frac{\gamma}{\rho g}}$$

and

$$y_1 = 6\sqrt{\frac{\gamma}{\rho g}}$$

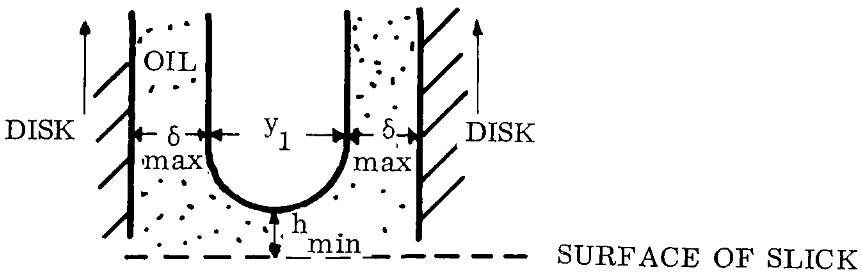


Figure 64. Boundaries Between Disks

The minimum spacing would then be

$$\delta_{min} = 2\,\delta_{max} + y_1 = \sqrt{\frac{2\gamma}{\rho g}}\left[\sqrt{1+\xi_{max}} - 1 + 3\sqrt{2}\right]$$

For a deep slick, $\xi_{max} = 2\mu/\gamma\, \omega C$, which is the worst case.
With Bunker C the largest value of ξ_{max} is of the order of 200, and

$$\delta_{min} = \sqrt{\frac{2}{27.8}} \left[\sqrt{201} - 1 + 3\sqrt{2}\right] = 4.6 \text{ cm} = 1.8 \text{ inches}$$

Similarly the minimum spacing the thick layers of 40-weight and diesel oils are calculated to be:

Diesel Oil	0.98 cm	or 0.38 inch
40-Weight	3.4 cm	or 1.3 inch

It is noted that these minimum spacings are independent of the size of the disk. This means that the disk immersion chord to spacing ratio can be made quite large as the disk size is increased. For example, using a spacing of 2 inches and a disk immersion chord of 50 inches, this ratio is 25.

The significance of this ratio comes in when one compares the performance of a multi-disk system with a drum of the same diameter and with the same length in the longitudinal direction. Following the same procedure as with the disk the following equation for the pumping rate of a cylinder of radius R can be developed:

$$\frac{\mu}{\gamma}\sqrt{\frac{\rho g}{\gamma}}\,\frac{Q}{\omega} = \frac{1}{6\sqrt{2}}\left[1 - \left(1 - \frac{2\mu}{\gamma}\omega R\right)\sqrt{1 + \frac{4\mu}{\gamma}\omega R}\right]$$

A comparison with the pumping rate for a disk (immersed to C = 2R) shows that the two systems should be equivalent when the chord-to-spacing ratio is between 2.5 and 3.0. This means that at a ratio of 25 the disk system can pump ten times as much oil as a drum of the same diameter and length.

SECTION X

DESIGN APPROACH

Based on the analysis of Section IX, a design calculation procedure was developed. Calculations were made covering a wide range of each parameter, and the data tabulated. From this, performance envelopes were drawn for each of the three oil types tested. Following on this, specific design recommendations are made, and finally operational recommendations are made.

PERFORMANCE ENVELOPES FOR THE DISK SYSTEM

The design criteria were based on the non-dimensional disk pumping rate expression with the following parameters:

1. Dimension-less single disk pumping rate

$$\overline{Q} = \frac{\mu}{\gamma} \sqrt{\frac{\rho g}{\gamma}} \cdot \frac{Q}{C}$$

where

μ = Coefficient of viscosity

γ = surface tension

ρ = density

g = acceleration of gravity

C = disk chord at immersion depth

Q = pumping rate per disk (both sides)

2. Dimension-less disk rotation rate

$$\overline{\omega} = \frac{\mu}{\gamma} \omega C$$

where

ω = disk rotation rate

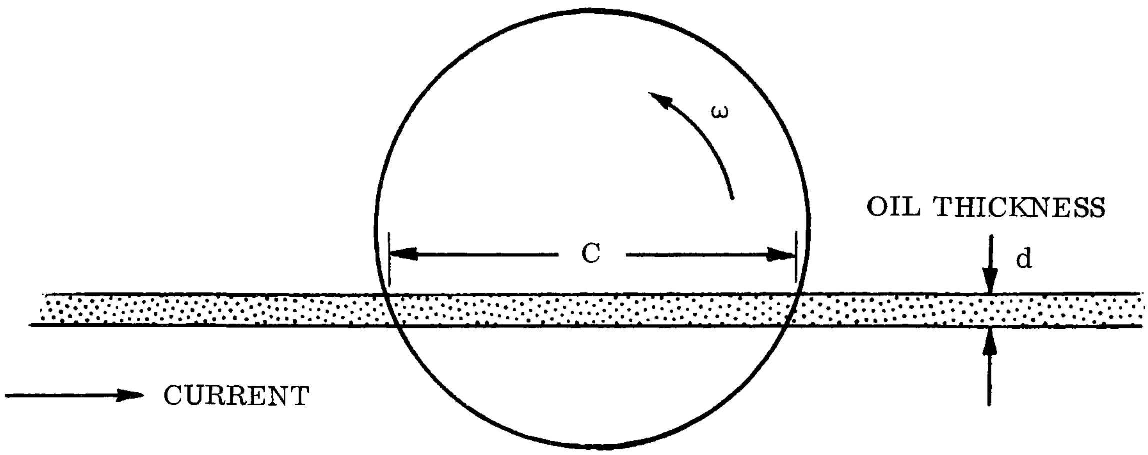


Figure 65. Model Disk

$\bar{Q}$ expresses the pumping rate on the assumption that the disk pump is "primed" properly and there is adequate in-flow of oil towards the disk. The flow field external to the disk which effects this "priming" condition has not been analyzed.

Water entrainment resulting from over-speed is empirically established from the experimental data in terms of a "critical rotation rate", $\bar{\omega}_{crit.}$, for each of the three oil types tested.

The incoming volume flow rate of oil per unit width of the oil front in a current is

$$V = Ud$$

where

U = current speed

d = oil thickness

If s = spacing between disks, the desired condition for a single pass clean sweep of the oil would require that

$$\frac{Q}{s} = V \doteq Ud$$

If the gross pumping speed of a disk array system is P.

$$P = \frac{Q}{s} L$$

where

L = length of array

and

$$N = \frac{L}{s}$$ (to nearest integer) is the number of disks

The spacing (s) cannot be arbitrarily small, because oil may completely fill the space between disks.

The properties of the three types of oil tested are listed below:

	Diesel	40-Weight	Bunker C
γ	28.5	30.0	34.6 dynes cm^{-1}
μ	4.2×10^{-2}	5.0	50.6 gm. cm^{-1} $sec.^{-1}$
ρ	0.842	0.895	0.979 gm. cm^{-3}
μ/γ	1.48×10^{-3}	1.67×10^{-1}	1.47 cm^{-1} sec.
$\rho g/\gamma$	2.90×10	2.93×10	2.78×10 cm^{-2}

Using these units, the units for Q and ω are ($cm.^3$ $sec.^{-1}$) and (radians. $sec.^{-1}$) respectively.

The limiting $\bar{\omega}$, for the threshold of water entrainment for the three oils, and the corresponding $\bar{Q}$ are:

	Diesel	40 Wt. Oil	Bunker 'C'
$\bar{\omega}_{crit.} = \left(\frac{\mu}{\gamma} \omega C\right)_{crit.}$	1.0	60	100
$\bar{Q}_{max.} = \left(\frac{\mu}{\gamma} \sqrt{\frac{\rho \cdot g}{\gamma}} \cdot \frac{Q}{s} \cdot \frac{s}{C}\right)_{max.}$	0.04	30	65

Specimen calculation for 40 Wt. oil

1. $\bar{\omega}_{crit.} = \left(\frac{\mu}{\gamma}\omega C\right)_{crit.} = 60$

2. $\bar{Q}_{max.} = \left(\frac{\mu}{\gamma}\sqrt{\frac{\rho g}{\gamma}} \cdot \frac{Q}{s} \cdot \frac{s}{C}\right)_{max.} = 30$

3. Let $U_{max} = 2$ knots $= 103$ cm./sec.

and $d_{max} = 1$ inch $= 2.54$ cm.

$$\left(\frac{Q}{s}\right)_{max} = V_{max.} = U_{max.} \times d_{max.} = 262 \text{ cm.}^2 \text{ sec.}$$

4. $$\left(\frac{s}{C}\right)_{max.} = \frac{\bar{Q}_{max.}}{\frac{\mu}{\gamma}\sqrt{\frac{\rho g}{\gamma}}\left(\frac{Q}{s}\right)_{max.}}$$

$$= \frac{30}{1.67 \times 10^{-1}\sqrt{29.3} \times 262} = 0.127$$

5. From 1/

$$(\omega C)_{crit} = \frac{60}{.167} = 360 \text{ cm. sec.}^{-1}$$

Let $\omega = 2$ rad. sec.$^{-1}$ $= 0.32$ revs. sec.$^{-1}$

Then $c = 180$ cm. $= 5.9$ ft.

Spacing $s = 0.127 \times C = 23$ cm. $= 9.0$ in.

6. $\rho_{design} = 50 \times 10^{3}$ gal hr.$^{-1}$

$$= 5.25 \times 10^{4} \text{ cm.}^{3} \text{ sec.}^{-1}$$

$$L = \frac{\rho_{design}}{\left(\frac{Q}{s}\right)_{max.}} = \frac{5.25 \times 10^{4}}{262} = 200 \text{ cm.} = 6.6 \text{ ft.}$$

$$N = \frac{L}{s} = \frac{200}{23} = 9$$

Pumping rate per disk

$$Q = \frac{Q}{s} \cdot \frac{s}{C} \cdot C = 26.2 \times 0.127 \times 180$$

$$= 6000 \text{ cm.}^{3} \text{ sec.}^{-1} = 5,700 \text{ gal. hr.}^{-1}$$

$$\text{Total } Q = 5,700 \times 9 = 51,300 \text{ gal. hr.}^{-1}$$

The important linear dimension with regard to oil pick-up is C, the wetted disk chord at immersion depth.

This chord dimension geometrically fits a disk diameter of 7.00 ft. and a disk immersion depth of 1.64 ft.

The above calculations were carried out for a series of current speeds, oil thicknesses and disk speeds of rotation for all three oil types, and were tabulated.

Graphs which form performance envelopes have been plotted from the tabulated data, and are presented. Figures 66, 67, 68 present plots of $(S/C_{max.})$ versus current speed for various oil thicknesses for 40 wt. oil, diesel oil and Bunker 'C' oil respectively

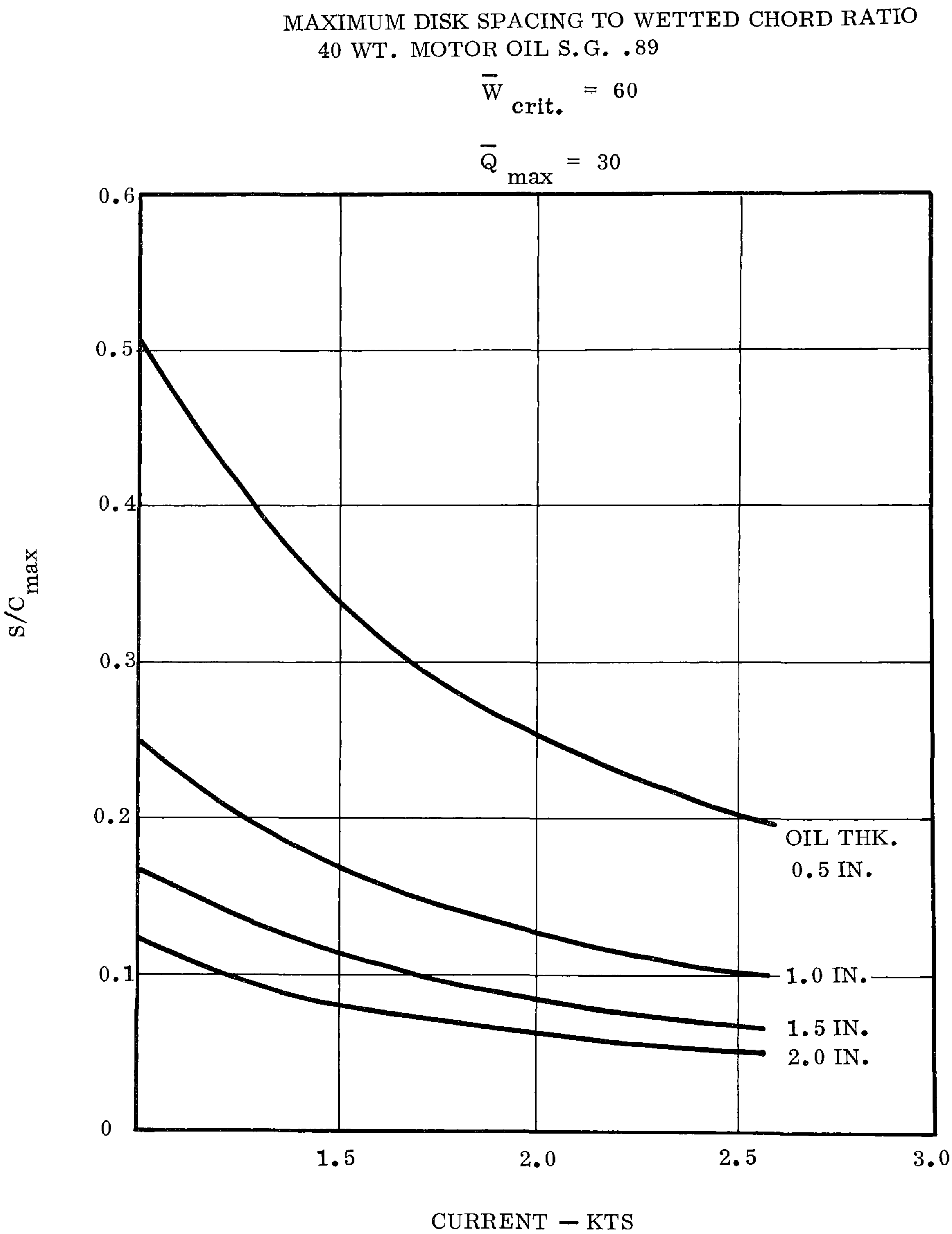


Figure 66. Oil Recovery System - Design Parameters

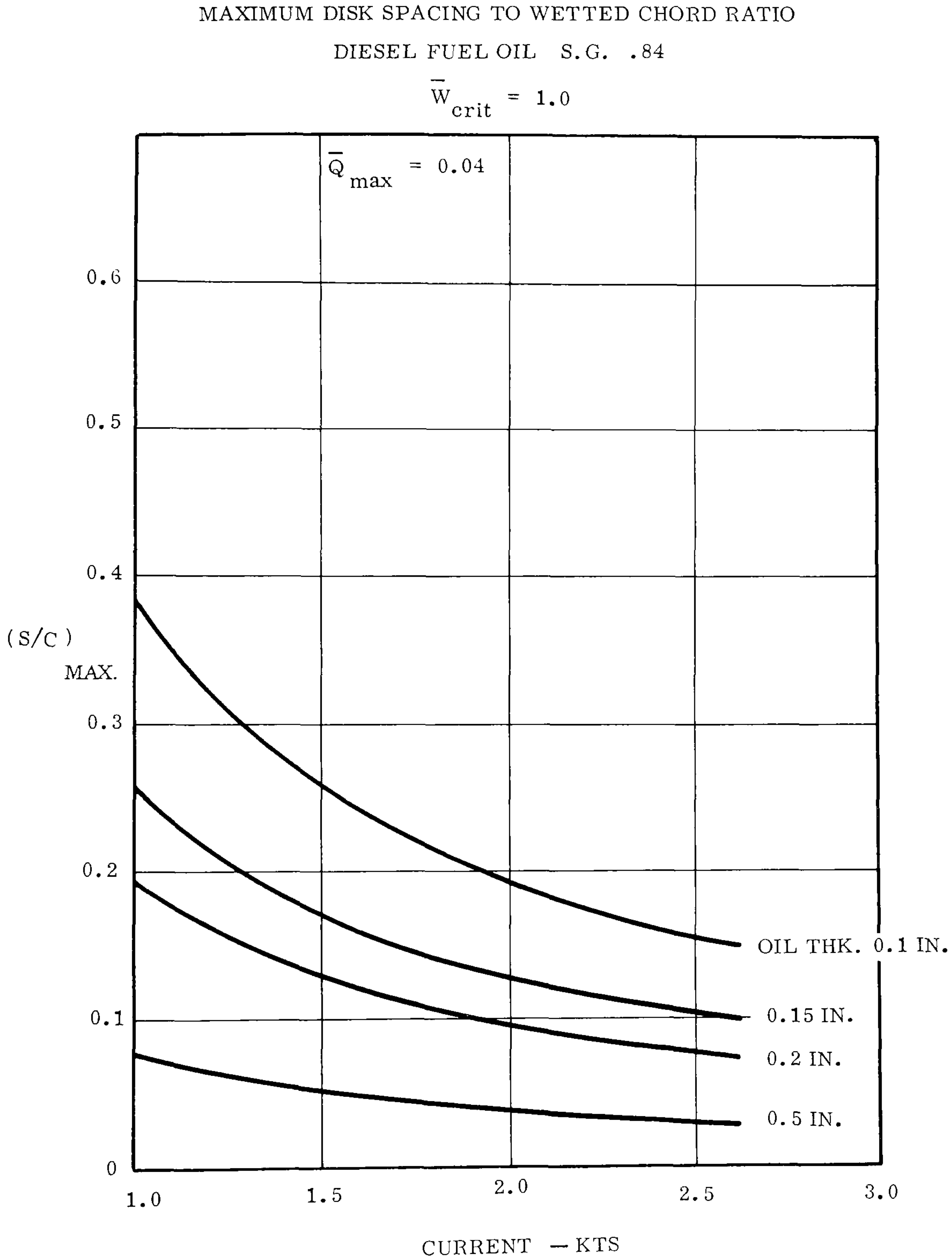


Figure 67. Oil Recovery System - Design Parameters

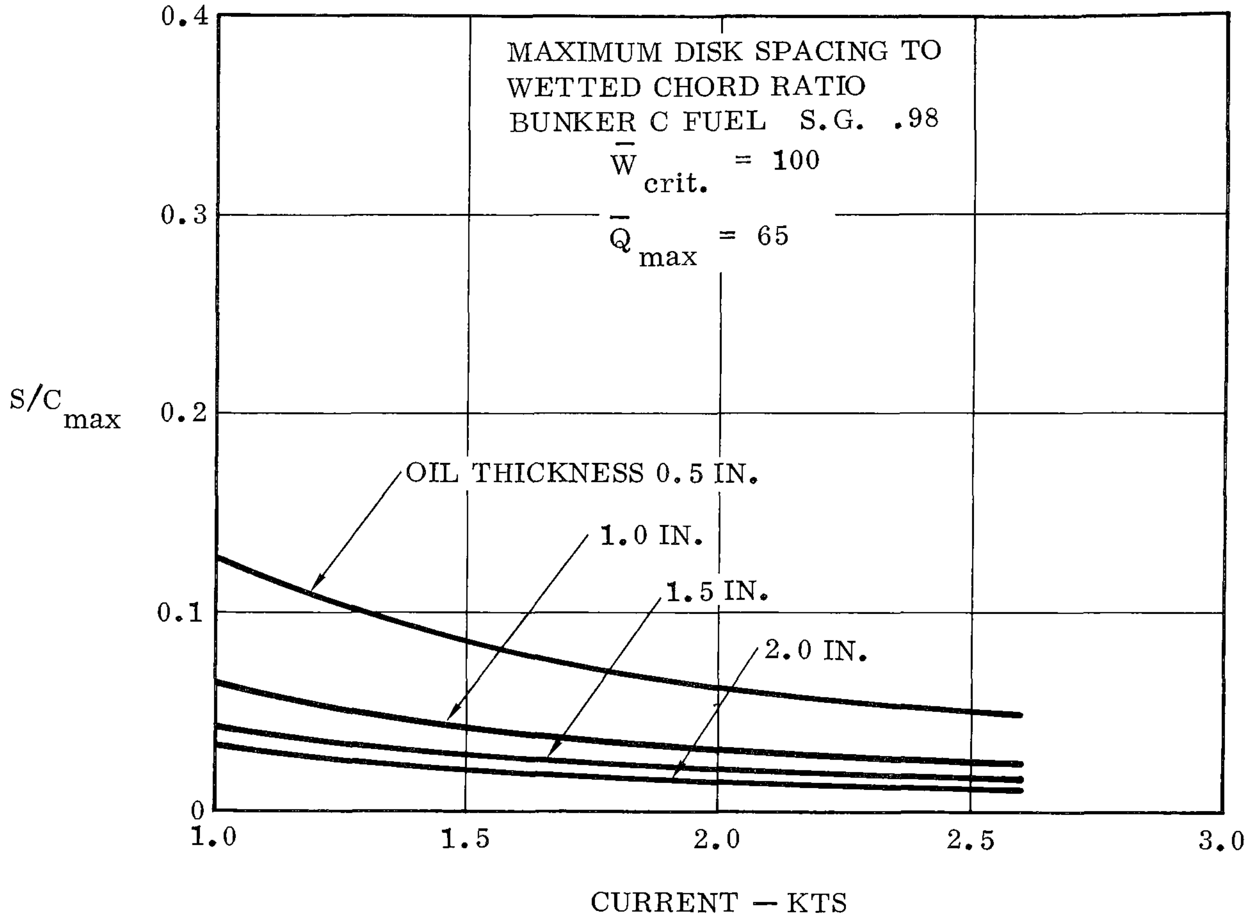


Figure 68. Oil Recovery System - Design Parameters

Figure 69 is a plot of disk spacing versus current speed for various oil thicknesses for 40 wt. oil. The oil pick-up for all points on the graph are 50,000 gallons/hour with zero water content, so any point is a possible design solution: Other fixed parameters are disk diameter 7.0 ft., number of disks 9, disk immersion depth 1.64 ft., and disk rotational speed 0.32 revs/sec. Figures 70, 71, 72, and 73 are similar plots for other fixed conditions and other oils, the actual conditions being printed on the figures.

Limiting values of disk spacing (s) are as follows:

Oil Type	Limiting (s)-in.	Limiting (s)-in. (with safety margin)
40 Wt.	1.3	2.0
Diesel	0.38	0.57
Bunker 'C'	1.8	2.7

Design solutions from the performance envelopes described, the following preliminary design recommendations are made.

Table 1. Case 1: Designs of Full Scale Systems for Thick Slick

R 3.5 FT. C 5.9 FT. Q_{Total} = 50,000 Gallons Per Hour

1.0 In. THICK	DIESEL (0.5 in. slick)	40 WT. SAE	BUNKER 'C'
MAX	1.0	60	100
Q_{MAX}	0.04	30	65
CURRENT	2	2	2 KNOTS
R.P.S.	0.60	0.32	0.06
Q (SINGLE DISK)	857	5,700	1,435
NO. OF DISKS	58	9	35
SPACING	2.72	9.0	2.27 INCHES
SYSTEM LENGTH (Not including disk thickness)	13.15	6.75	6.62 FT.
	Ref. Fig. 72	Ref. Fig. 69	Ref. Fig. 73

Table 2. Case 2: Designs of Full Scale Systems For Thin Slick

R 3.5 FT. C 5.9 FT. Q_{Total} 50,000 Gallons per hour

1mm SLICK	DIESEL	40 Wt. SAE	
crit.	1.0	60	
d	0.538	0.541	
max.	0.03	4.06	
CURRENT	2	2	KNOTS
R.P.S.	0.60	0.32	
(SINGLE DISK)	647	770	GAL. PER HOUR
MIN. SPACING (Based on Meniscus Study)	0.38	1.01	INCHES
NO. OF DISKS	78	65	
MIN. DISK SYSTEM LENGTH (Not incl. Disk Thickness)	2.5	5.5	FT.
FRONTAL HERDING WIDTH	168	168	FT.

For an operational system it is expected that a compromise system with fixed disk diameter, number of disks, and disk spacing will be used. Disk RPM and immersion depth would be made controllable.

FLOW DEFLECTORS

The assumption has been made in the analysis that there is an adequate inflow of oil towards the disk. The tests indicate that some means should be imposed on the external field to force oil flow normal to the disk, such as the one sketched on the following page. (Figure 74).

OPERATIONAL RECOMMENDATIONS

The disk system with a maximum span of 13.5 ft. should be rigidly attached to the bow of a tank barge 250 ft. x 44 ft. x 14 ft. 6 in. This size of barge is required from the craft motions point of view (see Section II). With a capability of 25,000 barrels of fuel oil it could operate with a powered disk system for up to 21 hours, working as an independent unit.

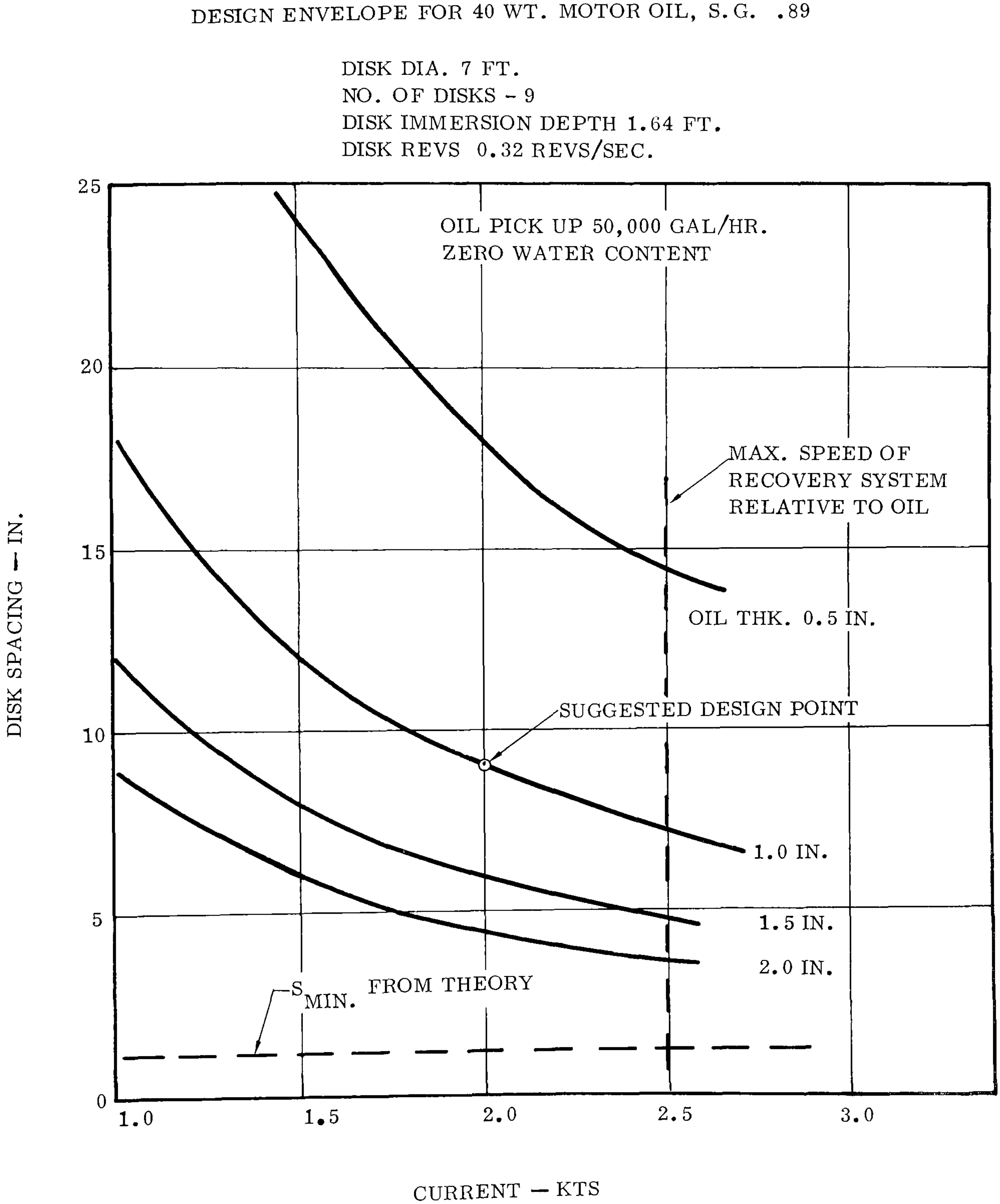


Figure 69. Oil Recovery System - Design Parameters

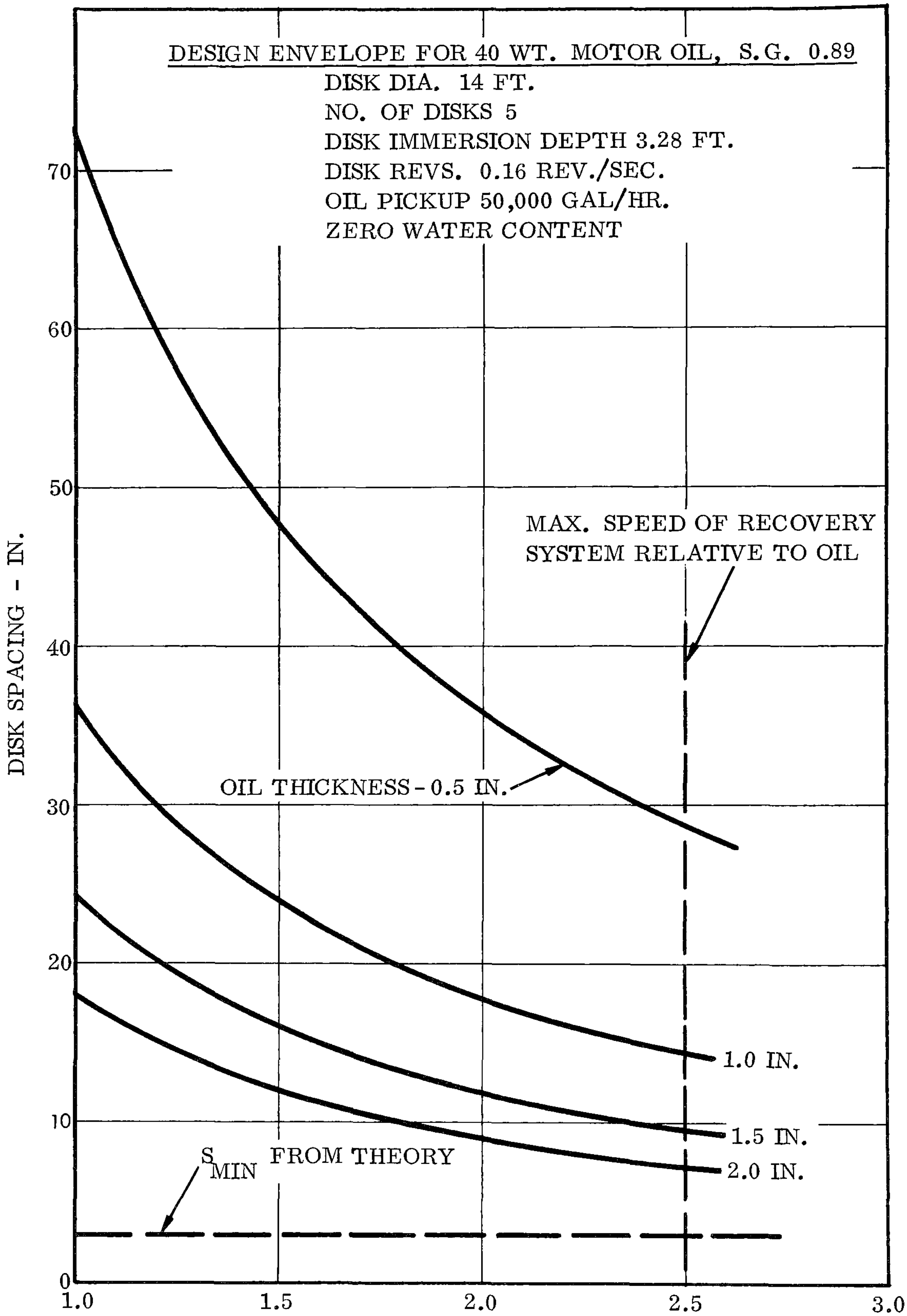


Figure 70. Oil Recovery System - Design Parameters

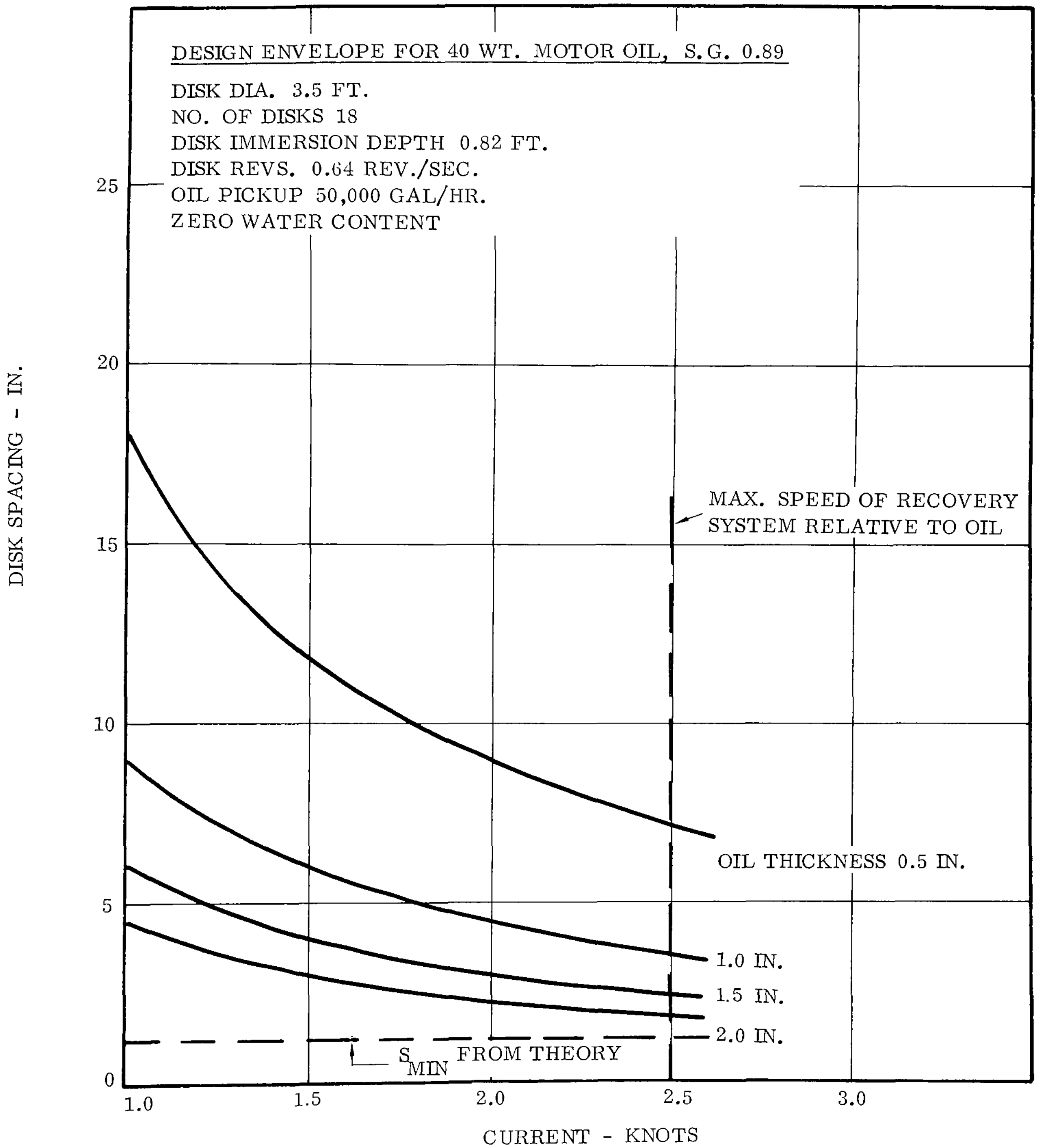


Figure 71. Oil Recovery System - Design Parameters

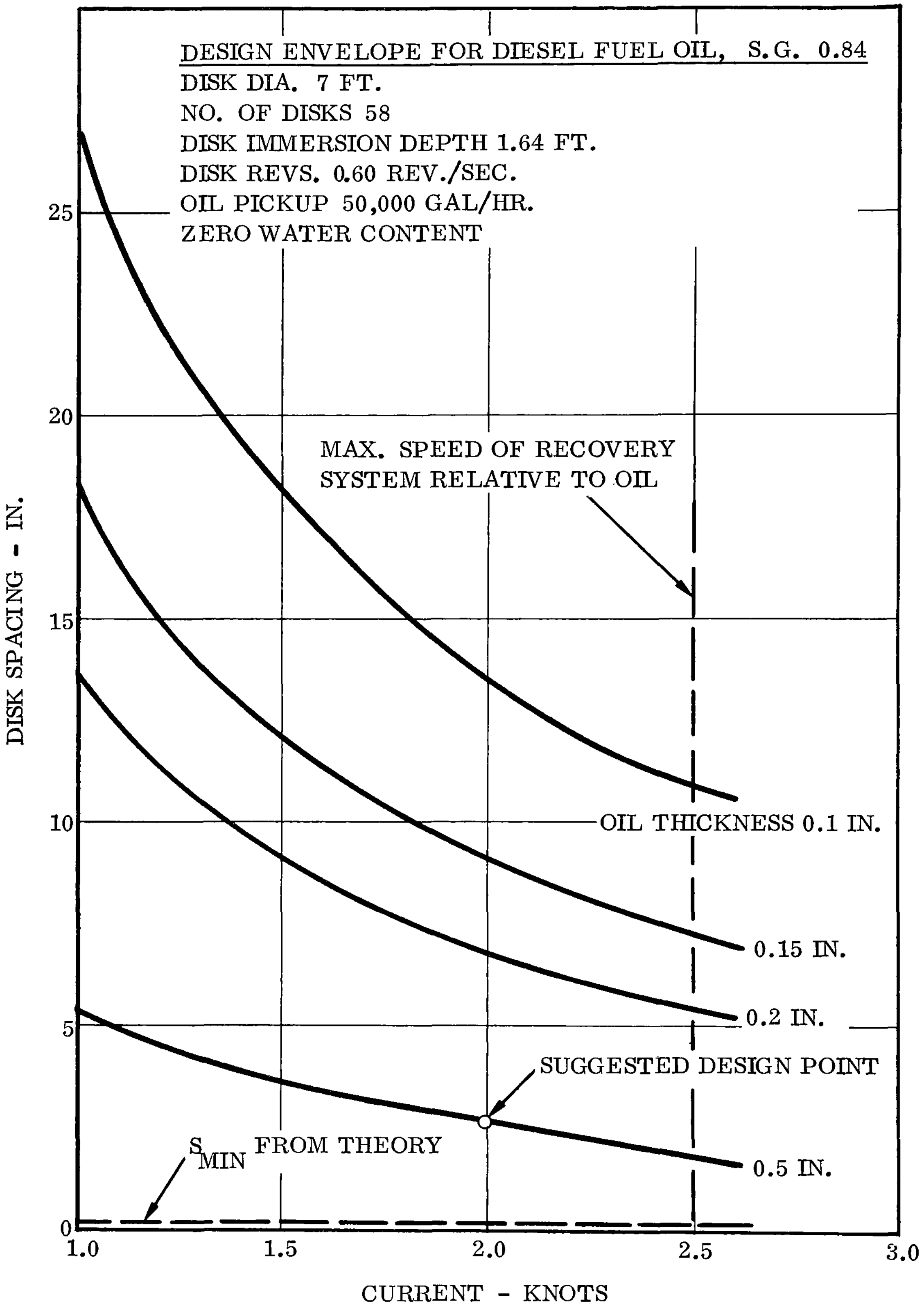


Figure 72. Oil Recovery System - Design Parameters

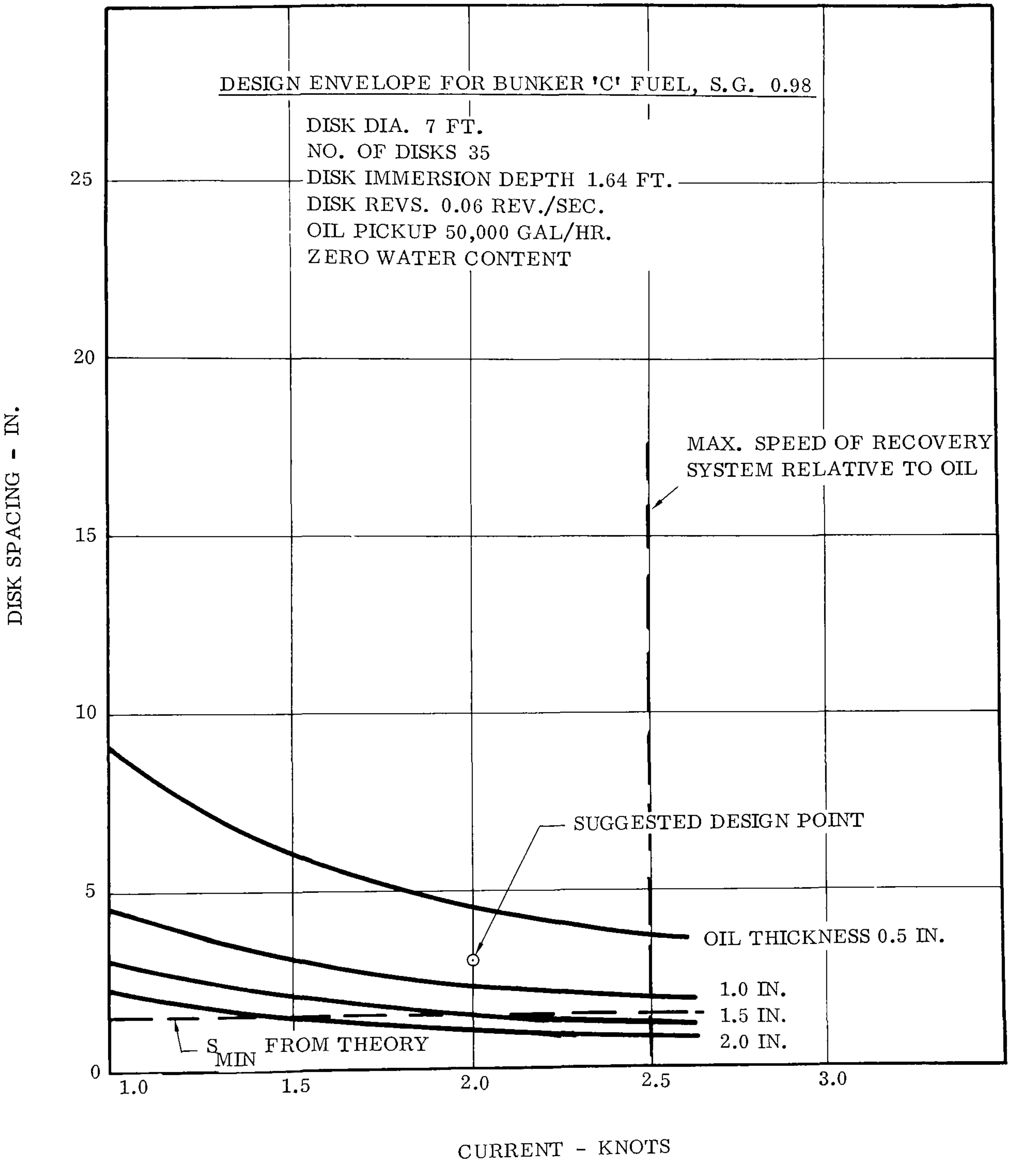


Figure 73. Oil Recovery System - Design Parameters

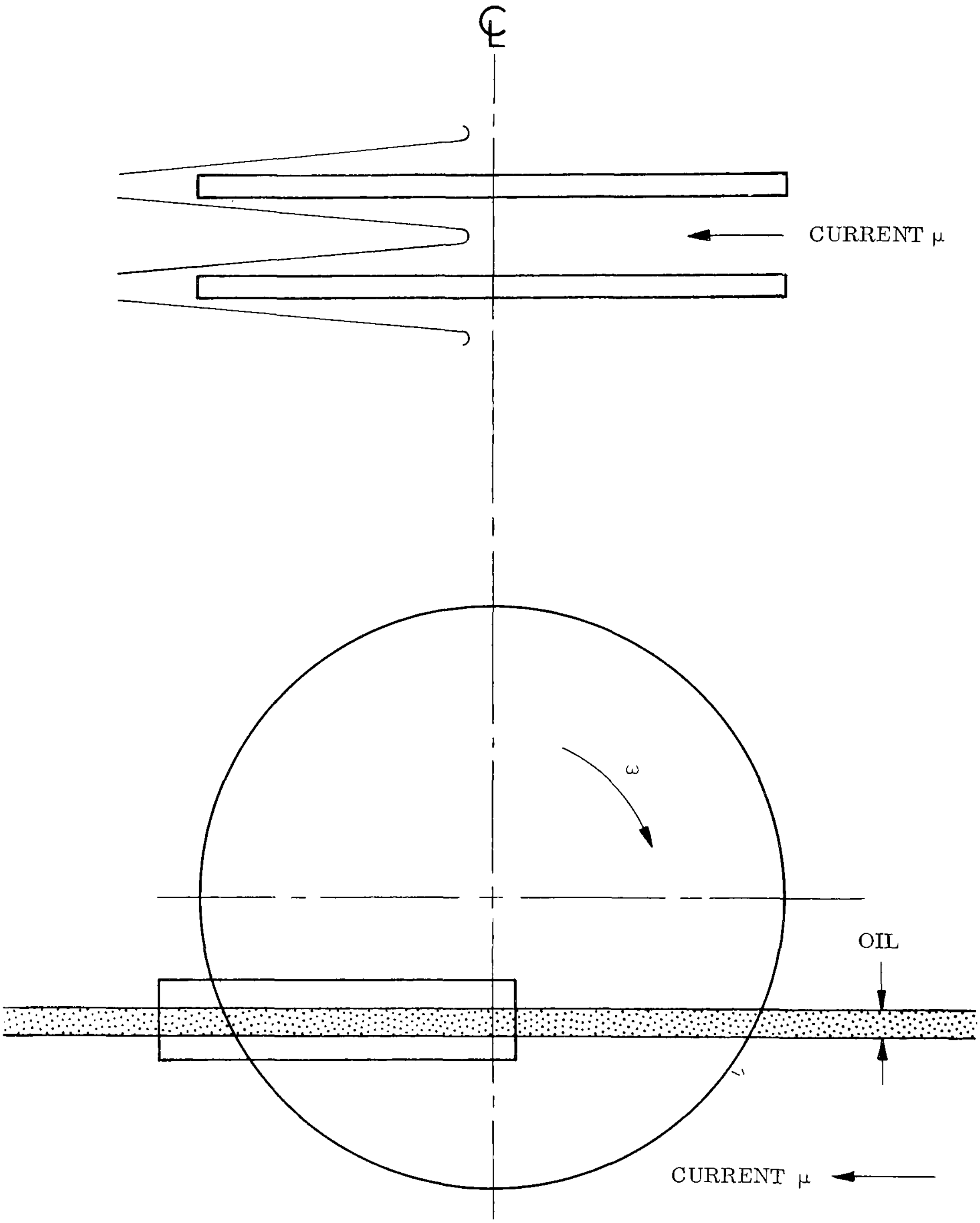


Figure 74. Disk with Deflectors

When working in a spill of crude oil or Bunker 'C' the disk-barge system would work without any herding arrangements. In a spill of oil equivalent to SAE 40 wt. motor oil it might have to operate within some sort of containment system, and would also probably be equipped with herding booms of its own as shown in the sketch below: (Figure 75).

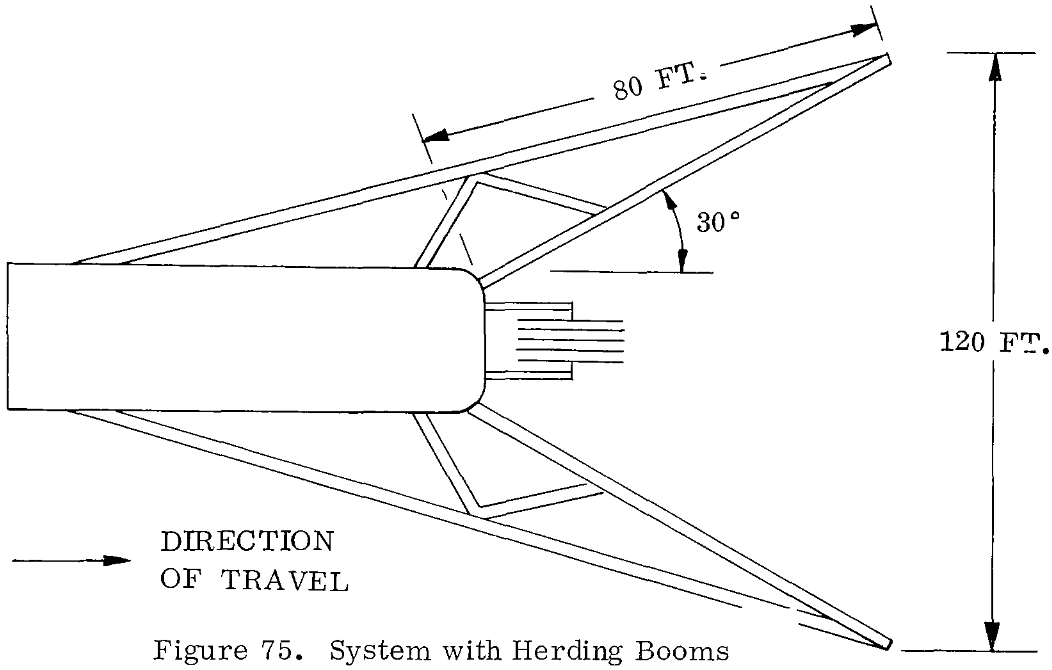


Figure 75. System with Herding Booms

In a spill of light diesel oil, the disk-barge system would probably have to be anchored at the apex of a much larger herding boom system as shown in the sketch below: (Figure 76). This is because diesel oil has such a high spreading rate, and in very thin slicks can only be picked up at a slow rate with high water content.

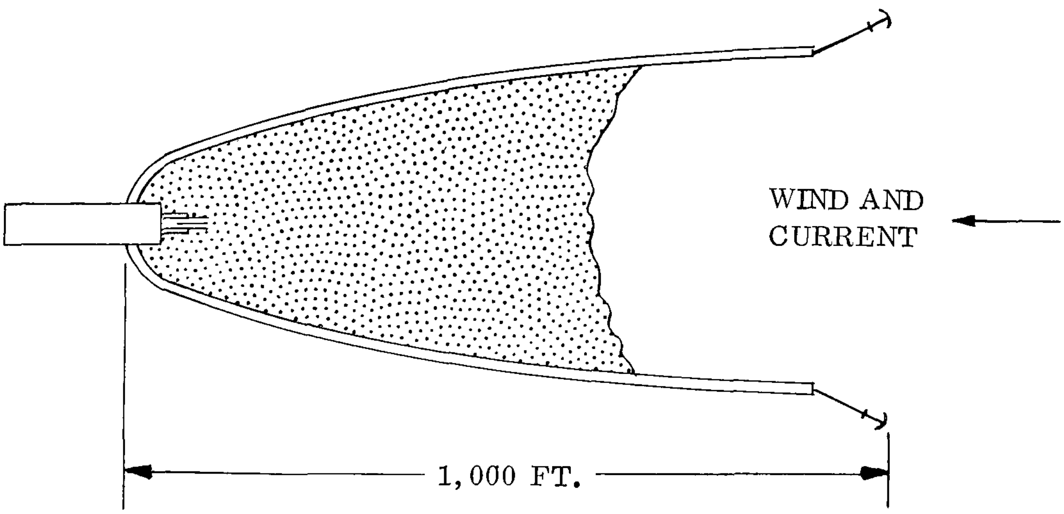


Figure 76. System with Anchored Booms

SECTION XI

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   Part I, Final Report, Volume I, June 1970. Prepared for U.S. Coast Guard Headquarters, Washington, D.C. Under Contract No. DOT-CG-04492-A by Atlantic Research, Costa Mesa, California.

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4. "Oil Spillage Study Literature Search and Critical Evaluation for Selection of Promising Techniques to Control and Prevent Damage" Report No. AD 666289, Battelle Memorial Institute, Richland, Washington, 20 November 1967.

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Pending Publication

"Concept Development of a Powered Rotating Disk Oil Recovery System", by A.C. Connolly and S.T. Uyeda, in course of preparation for the 1971 Conference on Prevention and Control of Oil Spills scheduled to be held in Washington, D.C. during June 15-17, 1971

SECTION XII

SYMBOLS

W	Disc rotational speed - rads/sec.
R	Disc radius
D	Immersed depth of disc
r	Some disc radius
θ	Angle subtended by line joining point where r intersects oil surface and center of disc, and the vertical
X	Horizontal distance from point where r intersects oil surface and center of disc
d	Oil depth at disc
C	Disc chord at the immersion line
δ	Boundary layer thickness of oil on disc
F_1, F_2	$= -\mu \frac{dV}{dy} dx\, dz$ Shearing forces
g	Acceleration due to gravity
μ	Viscosity of oil - gm. cm^{-1} sec.$^{-1}$
ϱ	Density of oil at edge of boundary layer
F_μ	$= -\mu \left(\frac{dV}{dy}\right) \delta\, h_\delta\, dx$ Shearing force
h_δ	Height of oil at edge of boundary layer above static level Surface tension of oil - dynes. cm^{-1}
Q	Volume of oil picked up by both sides of disc per unit time
L	Length along water line where oil is picked up $L = 2\left(\frac{C}{2} - X_\delta\right)$
S	Distance from disc center line to point where boundary-layer thickness is zero

$$\xi = \frac{4\mu}{\gamma} (\omega x - v_\delta)$$

δ_{max}	$= \frac{4\mu}{\gamma} \left(\omega \frac{C}{2} - V_\delta \right)$
$\bar{Q}$	Dimensionless disc pumping rate
	$= \frac{\mu}{\gamma} \sqrt{\frac{\rho g}{\gamma}} \frac{Q}{C}$
$\bar{W}$	Dimensionless disc rotation rate
	$= \frac{\mu}{\gamma} \omega C$
$\bar{d}$	Dimensionless slick thickness $= d \sqrt{\frac{\rho g}{\gamma}}$
h_{min}	Is the height of the oil fillet trough between two closely spaced discs
$_{min}$	Minimum disc spacing
V	Volume flow rate of oil per unit width of the oil front in a current
U	Current speed
s	Spacing between discs
P	Gross pumping speed of a disc array system
L	Length of disc array
N	Number of discs

SECTION XIII

APPENDICES

APPENDIX I

MATERIAL EVALUATION BASIC DATA

PHASE I MATERIAL EVALUATION

Water Wetted Samples

Water Wetted Surfaces Mg Oil/sq in Dry Basis

	Teflon	Polycarbonate	Polypropylene	Polyethylene	Neoprene	Al	Mild Steel	SS
Diesel	9.6	6.1	2.0	17.5	20.4	1.9	3.2	5.4
	10.4	7.4	2.4	61.7	15.1	.6	3.0	2.8
	14.6	6.5	2.1	19.4	19.0	3.1	4.8	5.6
	13.3	6.5	1.6	16.5	25.2	3.3	4.6	3.4
	10.0	4.6	6.1	17.6	19.4	2.4	3.6	4.5
	8.8	4.1	11.6	14.0	13.4	3.8	5.3	4.8
	11.8	3.5	6.4	15.9	19.3	2.8	4.2	6.8
	8.2	5.2	7.0	17.3	-	3.1	2.3	2.5
	7.6	2.5	3.5	16.0	11.6	2.2	3.0	3.4
	8.1	4.9	6.6	17.1	10.1	2.3	2.3	3.3
	7.7	3.1	5.8	17.5	11.1	2.1	3.2	2.9
	7.3	3.0	8.1	-	10.5	3.1	3.6	2.6
Median	9.8	4.8	6.0	17.3	15.1	2.6	3.6	3.4
Bunker C	384	206	391	594	437	536	422	527
	337	154	314	378	507	235	765	356
	409	174	432	510	452	341	354	427
	301	196	603	490	314	449	529	319
	344	186	570	387	237	459	232	357
	404	210	243	529	548	382	452	222
	423	212	262	450	488	263	350	246
	552	475	618	494	302	362	418	296
	388	361	344	517	438	527	320	325
	566	370	370	566	528	492	278	271
	639	418	266	622	439	333	326	382
	480	-	483	681	497	572	306	369
Median	408	210	412	523	448	415	338	322
Crude	132	81	177	309	294	211	248	84
	136	105	126	243	212	213	205	159
	85	89	122	225	269	185	169	151
	140	97	174	275	225	245	210	172
	164	115	145	345	268	140	140	222
	117	105	-	240	246	117	212	243
	107	122	124	171	252	106	-	196
	-	88	209	246	364	184		112
	125	98	196	302	320	322	121	150
	168	93	194	249	280	218	85	128
	127	114	277	273	223	146	185	90
	121	119	361	409	203	253	94	190
Median	132	101	177	285	259	248	177	155

Water Wetted Samples

Water Wetted Surfaces % Oil Picked Up

	Teflon	Polycarbonate	Polypropylene	Polyethylene	Neoprene	Al	Mild Steel	SS
Diesel	77.6	47.2	26.4	90.6	94.6	37.6	18.1	28.4
	73.1	46.0	44.9	95.7	88.6	27.2	16.1	21.8
	61.2	34.4	34.4	95.7	80.7	-	26.1	37.4
	72.8	47.8	33.1	98.0	87.8	43.7	24.3	17.8
	71.8	29.4	20.1	96.1	89.3	47.2	25.7	27.2
	48.6	48.6	35.1	93.3	84.4	23.7	26.3	38.8
	25.0	38.8	28.4	96.7	87.5	41.6	26.4	43.0
	72.8	38.9	46.7	95.6	-	39.6	15.1	13.3
	76.2	48.1	12.1	96.9	62.5	28.9	25.1	14.4
	73.7	58.2	15.8	91.8	76.2	43.8	15.6	16.0
	82.2	56.2	19.8	93.8	57.8	25.9	20.7	14.1
	74.1	69.8	11.1	90.8	68.4	42.6	21.8	13.3
Median	73.3	47.9	31.0	96.1	80.7	37.6	24.2	22.5
Bunker C	98.7	96.6	97.6	96.6	97.6	98.0	97.3	98.5
	98.9	96.3	99.1	96.1	96.8	95.5	97.8	97.9
	98.7	95.1	98.7	99.8	98.4	97.3	97.5	98.2
	97.9	98.5	96.3	99.1	96.3	98.1	98.5	97.8
	98.4	96.6	99.2	99.4	94.9	96.3	96.4	98.1
	98.9	98.1	94.7	99.3	98.3	97.4	98.1	96.4
	98.9	99.3	96.3	99.5	98.7	96.8	97.8	98.3
	97.4	98.9	98.3	99.2	96.6	96.6	98.0	96.4
	97.2	99.0	97.8	99.0	97.9	98.1	96.9	96.9
	98.4	98.3	97.9	98.8	98.5	97.2	94.8	95.4
	99.0	98.7	97.1	99.2	98.9	97.2	96.6	95.6
	98.7	98.2	98.5	99.1	98.2	97.9	95.9	96.9
Median	98.7	98.5	98.1	99.3	98.4	97.7	97.7	98.0
Crude	95.1	93.3	95.0	97.1	97.3	93.5	97.4	85.8
	96.5	94.9	91.1	96.2	95.0	95.7	94.9	90.6
	96.0	96.0	92.6	97.4	93.6	93.5	96.0	88.5
	95.2	95.0	98.7	96.6	96.5	96.2	92.4	92.4
	95.8	96.3	91.9	98.5	96.6	92.2	92.1	94.3
	94.4	93.5	91.3	96.7	93.0	92.5	96.3	95.0
	93.0	94.1	92.8	95.7	95.7	91.7	-	95.0
	-	93.5	93.7	97.6	95.3	95.4	-	95.2
	96.3	96.4	97.5	97.0	94.4	97.3	93.7	96.8
	96.8	95.1	95.6	-	96.4	91.5	90.2	93.5
	95.9	96.6	96.9	97.2	95.0	96.0	95.0	93.0
	96.8	95.7	96.8	98.7	94.2	97.0	93.7	96.3
Median	96.0	95.7	94.6	97.2	95.4	95.1	94.4	93.[illegible]

PHASE II MATERIAL EVALUATION

Oil Wetted Samples

Oil Wetted Surfaces   Mg Oil/sq in   Dry Basis

	Teflon	Polycarbonate	Polypropylene	Polyethylene	Neoprene	Al	Mild Steel	SS
Diesel	13.6	3.1	21.9	16.9	25.4	23.8	15.9	18.7
	12.6	6.0	17.4	18.1	24.2	23.3	19.8	17.4
	12.9	6.2	20.7	18.4	29.4	26.3	17.6	16.9
	13.6	3.6	20.9	21.1	23.6	22.4	20.6	18.8
	11.9	7.3	24.5	18.9	20.3	22.0	17.9	15.8
	10.0	5.4	24.4	20.5	23.0	26.9	16.7	18.3
	14.3	4.6	29.3	24.5	24.1	30.7	20.4	19.4
	10.7	14.3	30.3	20.5	18.6	23.5	22.3	19.1
	12.9	11.0	28.7	19.3	17.8	24.5	23.0	13.8
	12.5	12.2	25.4	21.2	19.3	23.8	17.4	20.0
	13.0	12.7	26.8	20.6	25.8	21.3	22.3	14.7
	10.5	12.3	25.9	21.3	24.1	24.1	19.7	22.4
Median	12.8	6.8	24.6	20.6	23.9	24.1	19.8	18.8
Bunker C	700	680	693	586	677	691	590	688
	661	743	649	738	633	532	586	672
	506	708	643	615	728	570	547	711
	874	721	758	747	662	614	638	732
	685	829	746	677	611	600	697	569
	694	815	496	614	716	553	661	657
	719	820	584	635	865	709	544	640
	743	691	664	693	717	767	469	541
	675	742	657	557	669	605	561	454
	578	671	665	651	650	697	569	536
	611	703	677	623	668	640	561	567
	736	720	586	517	755	537	526	493
Median	710	721	661	629	673	610	565	656
Crude	345	398	378	493	523	357	498	459
	347	387	378	541	547	458	469	470
	356	421	365	525	497	396	412	468
	315	473	398	416	534	437	518	465
	395	427	373	399	504	385	579	467
	368	417	374	391	565	338	476	434
	343	415	388	437	553	485	481	517
	469	380	354	403	588	369	510	514
	516	505	508	544	638	376	508	546
	473	441	573	542	498	434	480	545
	475	513	505	471	579	414	517	480
	456	452	540	580	559	416	422	472
Median	382	424	383	482	556	405	491	475

Oil Wetted Samples

Oil Wetted Surfaces % Oil Picked Up

	Teflon	Polycarbonate	Polypropylene	Polyethylene	Neoprene	Al	Mild Steel	SS
Diesel	84.7	38.3	51.9	91.4	96.8	93.2	89.3	83.9
	83.6	54.9	98.0	91.8	96.8	92.7	88.7	84.2
	85.4	59.1	50.2	89.2	96.3	91.3	85.2	83.0
	84.1	50.5	49.9	95.7	96.6	91.7	86.2	88.3
	83.0	57.4	54.5	91.1	95.0	91.8	92.8	83.4
	79.7	47.1	52.4	95.7	95.3	93.0	88.9	86.1
	87.2	47.6	55.2	93.6	94.8	92.9	87.7	85.3
	70.9	77.6	59.5	96.9	98.1	87.2	82.4	95.0
	69.9	71.3	56.4	85.4	94.8	91.3	97.3	85.9
	75.1	78.4	52.1	86.2	96.0	93.3	86.6	89.7
	79.1	74.5	54.5	80.2	93.8	91.1	91.2	86.5
	69.9	72.1	57.3	91.4	94.3	87.3	81.8	91.9
Median	81.6	64.4	53.4	91.6	96.4	92.2	88.7	87.1
Bunker C	99.9	99.6	99.8	99.8	99.8	99.9	99.8	99.8
	99.7	99.9	99.8	99.9	99.7	99.9	99.8	99.8
	99.9	99.9	99.8	99.8	99.6	99.9	99.8	99.8
	99.9	99.8	99.8	99.9	99.7	99.9	99.7	99.8
	99.9	99.9	99.8	99.8	99.6	99.9	99.8	99.9
	99.9	99.8	99.8	99.8	99.6	99.9	99.8	99.8
	99.1	99.6	99.7	99.7	99.5	99.9	99.9	99.8
	99.8	99.9	98.7	99.8	99.8	99.9	99.8	99.8
	99.8	99.6	99.6	99.8	99.4	99.9	99.7	99.6
	99.8	99.8	99.6	99.5	99.5	99.9	99.7	99.6
	99.8	99.9	99.7	99.8	99.6	99.9	99.7	99.7
	99.8	99.8	99.6	99.7	99.4	99.9	99.7	99.6
Median	99.8	99.8	99.7	99.8	99.6	99.9	99.8	99.8
Crude	99.4	98.4	98.4	99.6	98.9	99.3	99.6	99.4
	89.2	98.4	98.9	99.5	99.4	99.2	99.4	99.4
	98.5	98.8	98.9	99.2	99.4	99.3	99.6	99.3
	99.3	98.9	98.5	99.2	99.2	98.7	99.4	99.4
	99.5	98.7	98.4	99.4	98.7	99.2	99.6	98.7
	99.2	98.2	98.5	98.8	99.2	99.3	99.5	99.6
	98.7	98.5	98.6	98.6	99.5	99.3	99.3	99.5
	99.6	98.2	98.5	98.7	99.3	99.3	99.4	98.9
	99.1	99.0	99.0	99.1	99.2	99.2	99.4	98.9
	99.0	99.0	99.3	98.8	99.5	99.2	99.4	98.8
	99.0	99.3	98.6	99.0	99.4	99.4	99.4	99.2
	99.0	98.3	99.0	99.0	99.4	99.2	99.5	98.6
Median	99.3	99.8	98.9	99.1	99.4	99.3	99.4	99.3

PHASE III MATERIAL EVALUATION

ALUMINUM EVALUATION APPENDIX I

Al Pick-up Vs. Varying Concentrations of Bunkers Diesel

% Oil Dry Basis

Bunker C	90/10	75/25	62.5/37.5	50/50	32.5/62.5	.25/75	Diesel
	99.8	99.1	98.3	96.6	95.5	94.7	
	99.7	99.1	98.8	97.3	93.7	94.2	
	99.7	98.6	98.7	96.3	94.9	94.7	
	99.7	99.3	98.6	97.1	95.0	94.7	
	99.6	98.9	99.1	95.9	96.4	93.7	
Median 99.9	99.7	99.5	98.7	96.6	95.3	94.6	92.2

Al Wt Pick-up/Sq In Varying Concentrations Bunker C - Diesel

Mg/Sq In Dry Basis

Bunker C	90/10	75/25	62.5/37.5	50/50	32.5/62.5	.25/75	Diesel
	311	161	64.2	45.9	44.3	28.3	
	295	129	73.2	48.2	37.0	26.6	
	288	130	80.9	47.1	36.5	26.4	
	339	166	76.4	44.0	38.9	28.8	
	333	133	82.0	53.5	33.3	24.8	
	309	133	81.3	51.5	40.3	29.0	
Median 610	310	133	78.7	47.7	38.0	27.0	24.1

APPENDIX II

LABORATORY RESULTS OF OIL PROPERTIES

TRUESDAIL LABORATORIES, INC.

HEMISTS MICROBIOLOGISTS ENGINEERS
'ESEARCH - DEVELOPMENT TESTING

4101 N. FIGUEROA STREET
LOS ANGELES 90065
AREA CODE 213 • 225-1564
CABLE TRUELABS

CLIENT Atlantic Research
3333 Harbor Blvd.,
Costa Mesa, California 92626
Attention: Mr. Tom Fralia

DATE September 15, 1970

RECEIVED September 3, 1970

SAMPLE 10 Oils as shown

LABORATORY NO. 104561

P.O. No. 1011-T

INVESTIGATION Determination of viscosity, surface tension and density.

RESULTS

Sample Identification	Viscosity @ 25°C Centistokes	Surface Tension @ 25°C dynes/cm	Density @ 25°C
Diesel	4.2	28.5	0.8420
75/25 C/Diesel	490.	30.0	0.9393
25/75 C/Diesel	43.1	28.4	0.8701
Crude	2458.	31.7	0.9561
62.5/37.5 C/Diesel	107.9	29.7	0.9260
Bunker "C" from tank	7746.	35.2	0.9812
Bunker "C"	5056.	34.6	0.9790
50/50 C/Diesel	80.2	29.5	0.9045
90/10 C/Diesel	1073.	31.4	0.9603
35.5/62.5 C/Diesel	45.1	28.8	0.8862

Respectfully submitted,

TRUESDAIL LABORATORIES, INC.

A. W. Zahner, M.S.
Chief Chemist

1 Accession Number	2 Subject Field & Group	
W	05G	**SELECTED WATER RESOURCES ABSTRACTS** INPUT TRANSACTION FORM

5 *Organization*

Atlantic Research, Marine Systems Division
Costa Mesa, California 92626

6 *Title*

RECOVERY OF FLOATING OIL: ROTATING DISK TYPE SKIMMER

10 *Author(s)*

16 *Project Designation*

EPA, WQR Contract No. 14-12-883

21 *Note*

22 *Citation*

23 *Descriptors (Starred First)*

*Oil, *Oil Wastes, *Oily water

25 *Identifiers (Starred First)*

*Oil Recovery, *Rotating Disks, Experimental Model, Floating Oil

27 *Abstract*

Laboratory tests of disc materials in oils ranging from light diesel to Bunker 'C' indicated that aluminum was the best overall. Experimental tests on model discs in still water established baseline performance data and understanding of scaling effects. Established that oil starvation between discs is a problem, but that percentage of water in recovered oil is less than 2% except for Bunker 'C' oil, and other oils in 2mm thickness slicks. Experimental tests of multiple discs in a towing basin established the effects of current and disc spacing, and showed that the rotational velocity vector in the fluid should be in the same direction as the current flow. Non-breaking waves have little effect on oil pick-up rate. The design method developed by comparison between theoretical analysis and experimental data shows that the overall size of the disc unit would be 7 foot diameter by 12 foot for recovery of 50,000 gallons per hour.

Abstractor S. T. Uyeda | *Institution* Atlantic Research Corp.