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HIGH SPEED VACUUM PERFORMANCE OF MINIATURE BALL BEARINGS LUBRICATED WITH COMBINATIONS OF BARIUM, GOLD, AND SILVER FILMS

by Thomas W. Flatley

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SUMMARY

This report describes the second phase of a program involving metallic film lubrication of miniature ball bearings for vacuum use. Phase I involved bearings with gold-plated balls and raceways and was a retainer study which resulted in the selection of fully machined retainers of "S"-Inconel and silver-plated Circle "C" for use in this phase. Bearings with these retainer types and six ball and race plating combinations of barium, gold, and silver were studied in Phase II. They were run in pairs in small induction motors in a vacuum environment, with nominal test conditions of 10,000 rpm, no external loading, and an oil-free ambient pressure in the 10^{-7} torr range.

Testing revealed only one bearing configuration worthy of further study—that involving gold-plated balls, silver-plated raceways, and the fully machined silver-plated Circle "C" retainer. In direct contrast the combination of silver-plated balls and gold-plated raceways gave consistently poor performance. Bearing lifetimes achieved with the other configurations, all involving barium plating, in general fell between these extremes.

The next and final program phase planned is a metallurgical study, investigating the effects of variations in plating thickness and procedures on the performance of the three best bearing configurations found to date.

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INTRODUCTION

This report describes the second phase of a three part program involving metallic film lubrication of miniature ball bearings for vacuum use. Program philosophy and testing procedures were described in detail in a previous report covering Phase I of this study.*

Briefly, metallic film lubrication is being studied as a possible answer to the evaporation and radiation resistance problems experienced with conventional bearing lubricants in space. Bowden and Tabor† demonstrated that the use of low shear strength metallic films over relatively hard base metals can significantly reduce the coefficient of sliding friction between metals. The usefulness of this type of "lubrication" when applied to ball bearings is the subject under study in this program. This study is being conducted in conjunction with New Hampshire Ball Bearings, Inc., Peterborough, New Hampshire. The program is set up in three parts:

1. Phase I—retainer study, all balls and races gold plated.
2. Phase II—plating study, involving various combinations of ball and race platings in conjunction with a retainer selected from Phase I.
3. Phase III—metallurgical study, investigation of the effects of plating procedures, thickness, alloying, etc. on the performance of a bearing configuration selected from Phase II.

The test program involves running pairs of 1/8 in. bore bearings (Figure 1) in small 10,000 rpm induction motors (Figure 2) in a vacuum environment. The motors run until stalled and, since speed is a linear function of load, bearing performance can be observed by speed monitoring. Motor stall torque is on the order of 1/4 oz-in. A special multi-port vacuum system

*Evans, H. E., and Flatley, T. W., "High Speed Vacuum Performance of Gold Plated Miniature Ball Bearings, with Various Retainer Materials and Configurations," NASA Technical Note D-2101, December 1963.
†F. P. Bowden and D. Tabor, "The Friction and Lubrication of Solids" Oxford, England: Clarendon Press, 1950.

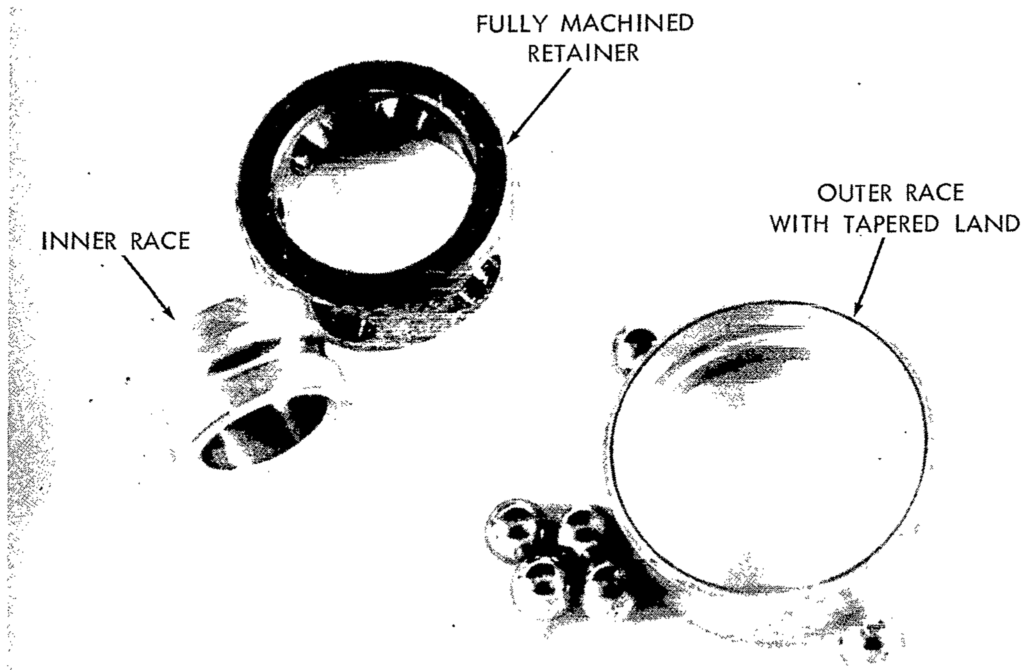

Figure 1—Typical set of bearing components.

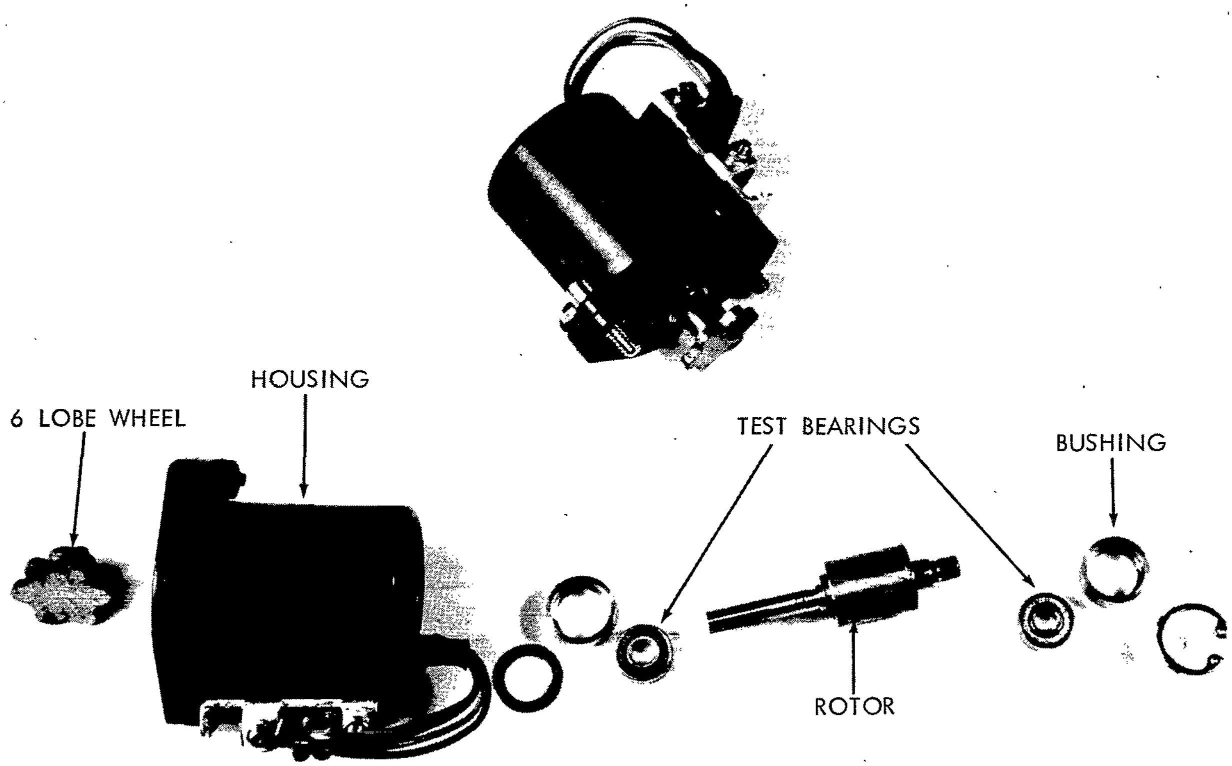

Figure 2—Assembled and disassembled motor for test setup.

(Figure 3) was designed and built for use in this program. It employs cryogenic roughing and the ion-getter type of high-vacuum pumping in order to eliminate the possibility of bearing lubrication by diffusion pump oil.

Figure 3—Vacuum system, bearing test program.

Phase I resulted in the choice of fully machined retainers of "S"-Inconel and silver-plated Circle "C" for use in the second phase of the program.

PHASE II PROGRAM

Gold, silver, and barium were the metallic lubricants involved in this part of the study. They were plated on 440C stainless steel balls and races. The gold and silver were electrodeposited to a nominal thickness of 30 microinches and the barium was applied by vacuum deposition, nominally 10 microinches thick.

The six possible permutations of ball and raceway platings and the two retainer types used resulted in the testing of twelve basic bearing configurations. In addition, bearings with gold-plated balls and silver-plated raceways, with the plating done by an alternate plater (designated "LR" in this report) were tested. In Table 1 the test results are presented in fourteen groups, divided according to the basic bearing configuration.

RESULTS

The results are presented in Table 1 and graphically in Figures 4-9. In the latter case tests are grouped according to both ball plating and raceway plating, for comparison purposes. Each test therefore appears twice in these figures.

During testing, mounting difficulties sometimes resulted in the outer race being slightly "out of round." This condition unfortunately did not show up until the bearings were autopsied. Tests which were obviously invalid due to improper mounting have been culled from the data so that the results as shown represent valid tests of the metallic film lubricants involved.

Tests 1, 2, 3, and 4 involved the unplated S-Inconel retainer, barium-plated balls and gold-plated races. These bearings had an initial radial play of 0.0002 to 0.0004 in. and rapid failures occurred in each test. None of the bearings had any measurable radial play remaining when they were autopsied. The longest run was only 13 hr and the autopsies revealed a large amount of gold transfer from the races to the balls where it accumulated irregularly, making them rough and eventually causing seizure because of a loss of internal clearance. The retainers in these bearings were relatively unaffected by the testing.

The bearings in tests 5 and 6 were similar except that the silver-plated Circle C retainer was used. Initial radial play was again 0.0002 to 0.0004 in. and again none remained after testing. In these tests the retainer played an important part in extending the bearing life by a factor of 4, compared with those previously discussed (Figure 4). Gold transferred from the raceways to the balls again, but some of it then re-transferred to the silver-plated retainer ball pockets, thus diminishing the rate of build-up, helping maintain some radial play, and extending the operating time. However, the longest run achieved was still only 42 hr.

Table 1

Bearing Configurations Tested and Phase II Test Results ("D" and "LR" designate two commercial plating sources).

Ball Plating	Raceway Plating	Retainer Type	Retainer Plating	Test	Running Time (hr)	Remarks
Barium	D Gold	S-Inconel	None	1	7	Gold build-up on balls
				2	13	Same
				3	10	Same
				4	5	Same
		Silver-plated Annealed Circle C	D	5	39	Gold and silver build-up on balls
				6	42	Same
	D Silver	S-Inconel	None	7	502	Heavy wear
				8	1012	Heavy wear and silver build-up on balls
				9	68	Silver flaking
		Silver-plated Annealed Circle C	D	10	63	Circle C debris and silver build-up on balls
				11	84	Same
				12	103	Same
				13	45	Same
D Gold	Barium	S-Inconel	None	14	48	Gold and S-Inconel build-up on races
				15	66	Same
		Silver-plated Annealed Circle C	D	16	164	Heavy wear
				17	410	Severe ball wear with silver build-up
				18	180	Heavy wear, silver build-up on races
				19	203	Same
	D Silver	S-Inconel	None	20	20	Gold build-up on races
				21	380	Same
				22	79	Same
				23	560	Severe wear
		Silver-plated Annealed Circle C	D	24	1307	Silver build-up on races
				25	41	Silver flaking
				26	757	Silver build-up on races
LR Gold	LR Silver	S-Inconel	None	27	2	Silver build-up on balls
				28	34	Same
		Silver-plated Annealed Circle C	LR	29	2404	Severe wear
				30	63	Silver build-up on balls
				31	518+	No failure but heavy wear
D Silver	Barium	S-Inconel	None	32	703	Silver build-up on races
				33	111	Same
				34	343	Flaking of silver build-up in retainer pockets
				35	161	Silver flaking
		Silver-plated Annealed Circle C	D	36	266	Silver build-up on races
				37	373	Flaking of silver build-up in retainer pockets
				38	325	Silver build-up on races
	D Gold	S-Inconel	None	39	100	Gold build-up on balls
				40	189	Same
				41	1	Silver flaking
		Silver-plated Annealed Circle C	D	42	40	Gold build-up on balls
				43	16	Same
				44	9	Same
				45	18	Same

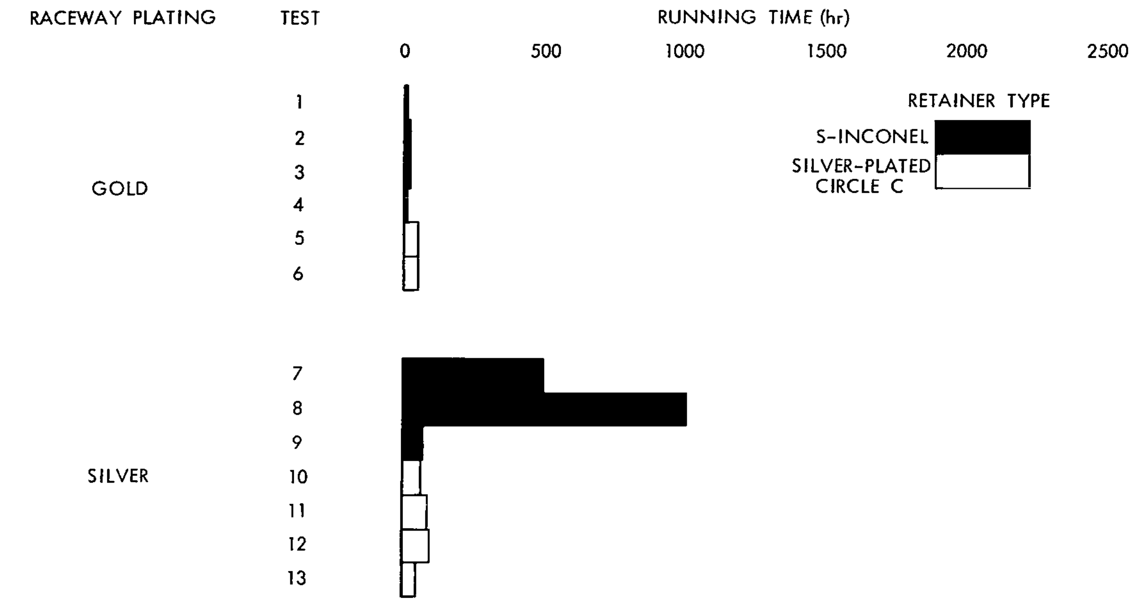

Figure 4—Test results, barium-plated balls.

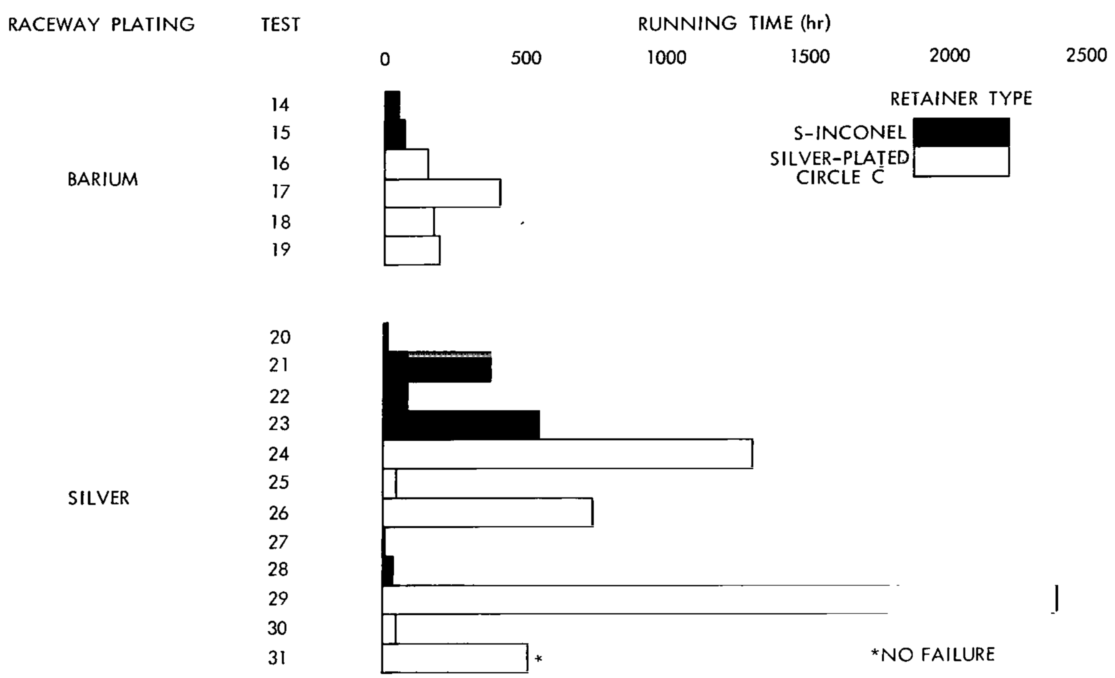

Figure 5—Test results, gold-plated balls.

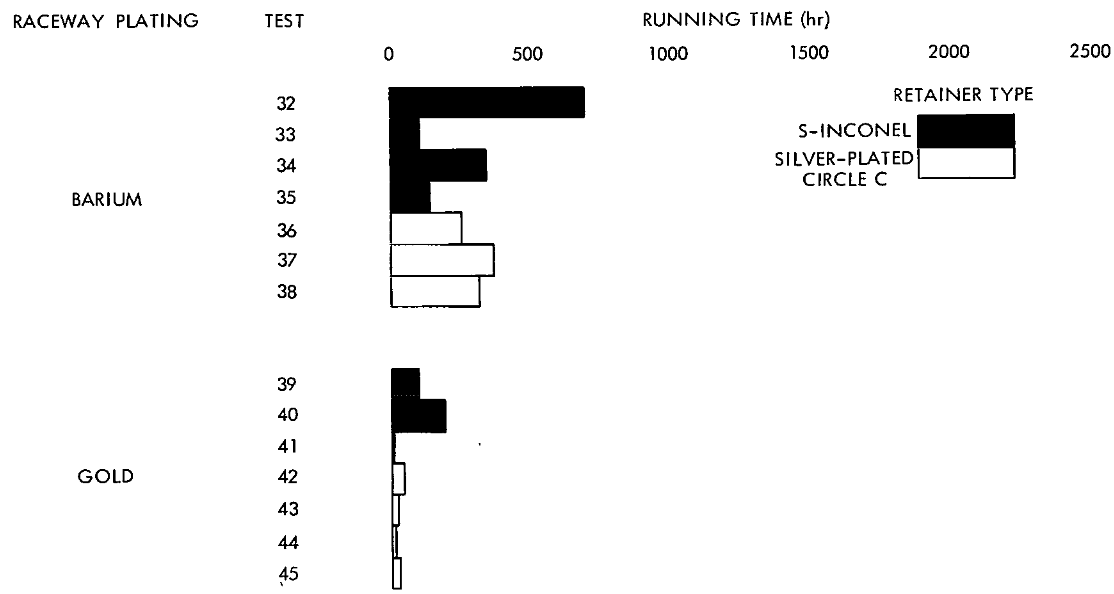

Figure 6—Test results, silver-plated balls.

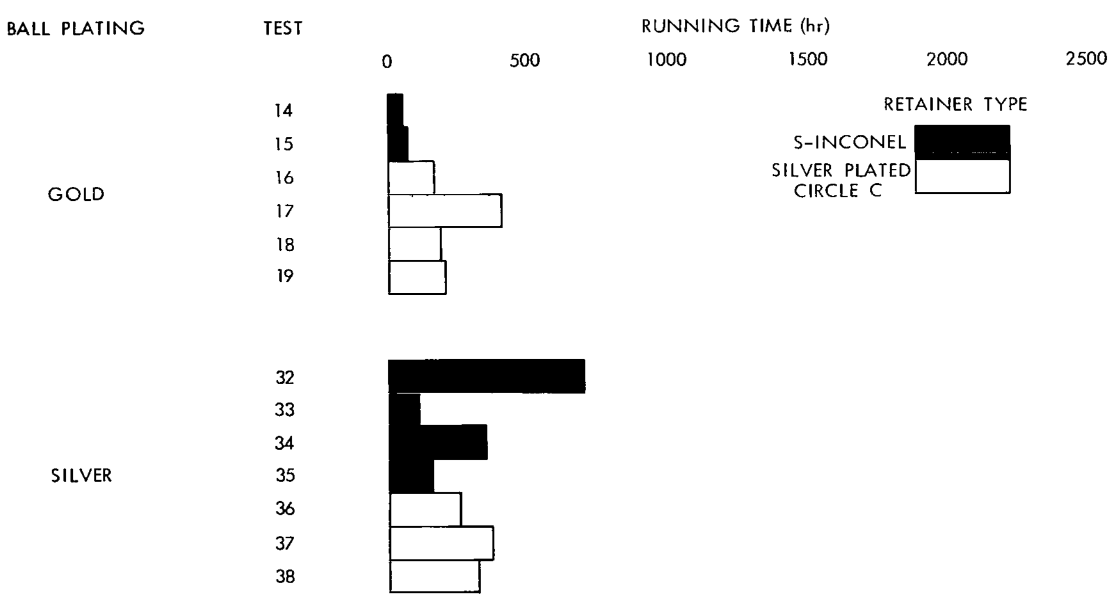

Figure 7—Test results, barium-plated raceways.

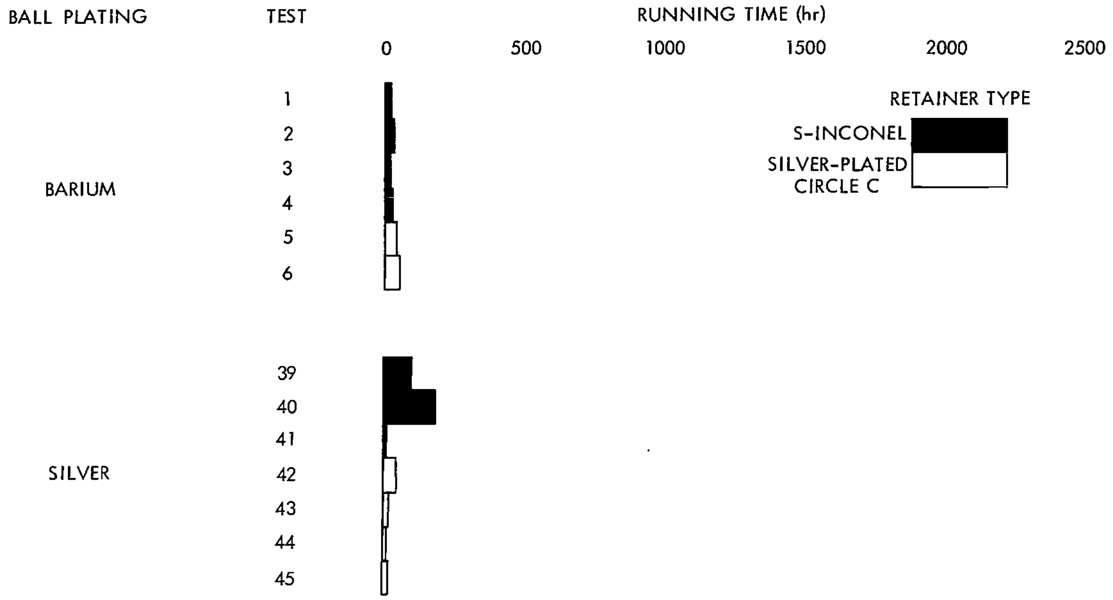

Figure 8—Test results, gold-plated raceways.

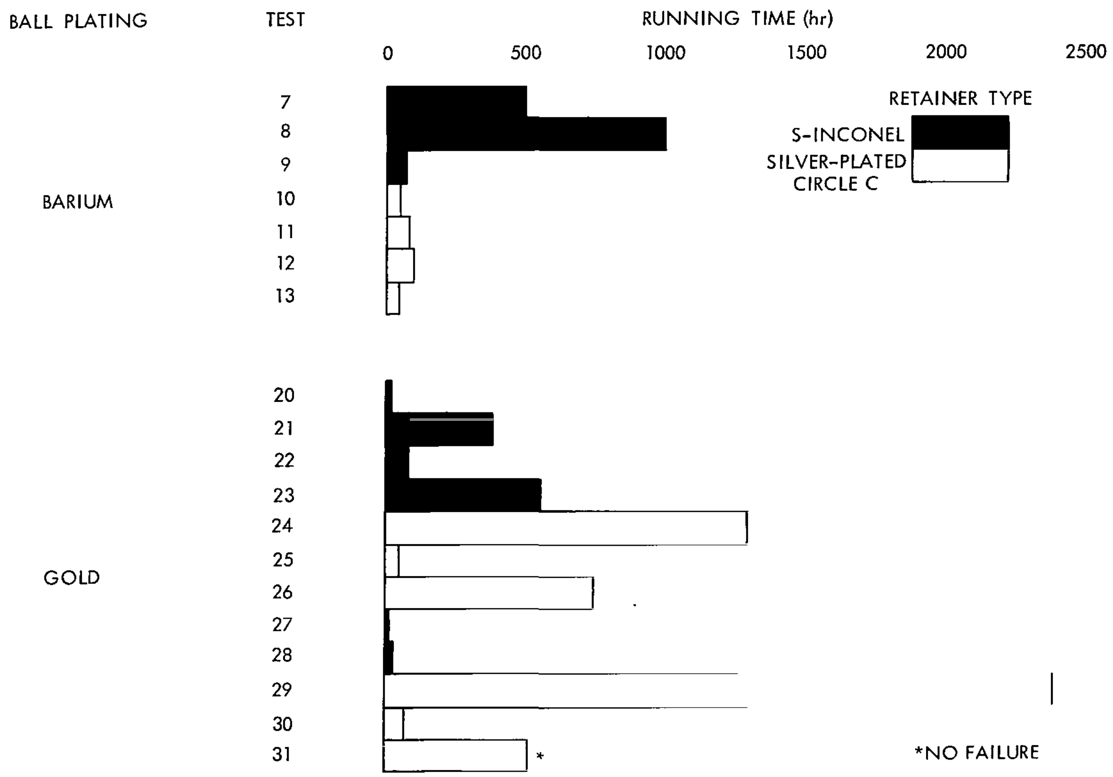

Figure 9—Test results, silver-plated raceways.

Tests 7, 8, and 9 involved bearings with barium-plated balls, silver-plated raceways, and the S-Inconel retainer. Initial radial play was greater (0.0004 to 0.0006 in.) than in previous tests. In all cases where measurement was possible after testing, it was as before found to be zero. Two long runs (500 and 1000 hr) and one early failure were experienced with this configuration. The premature failure in test 9 was caused by silver flaking in a raceway of one of the bearings. The other bearing appeared to be as good as new when autopsied. This failure points out a basic reliability problem with metallic film lubricated bearings. A local defect in the plating, possibly imperceptible under visual inspection, can cause catastrophic failure.

Heavy wear took place during the longer runs on all the bearing balls and races, but retainer damage was surprisingly slight. Apparently the silver remained intact on the raceways for a long period, during which the barium on the balls lubricated their sliding in the retainer ball pockets, so that little metallic transfer took place.

Some silver transfer was evident in the failed bearings however. The balls had areas of build-up, possibly in places where base metal had been exposed. Either transfer of this type or eventual local flaking of the silver probably led to a roughness in the bearing which caused the generation of debris and then failure. The damage to the contact surfaces experienced prevents anything more than speculation in this regard.

Tests 10, 11, 12, and 13 involved the same type of bearings with the same radial play range, but with the silver-plated Circle C retainer. Figure 4 shows the poorer performance of this configuration -the longest run was only 103 hr. In each of these tests, radial play was lost in one bearing but maintained at its initial value in the other, indicating that seizure occurred soon after the failure process began. Failure was caused by an irregular build-up of silver and Circle C on the balls, and extensive retainer damage took place.

Although they were compatible with the previously discussed S-Inconel retainers and did well when rolling on silver-plated raceways, the barium-plated balls, in sliding in these retainer ball pockets, caused considerable damage, generating both silver and Circle C debris. This debris caused removal of barium from the balls and permitted silver build-up and failure. In the better of the two bearings in each test, this process had not advanced so far.

Tests 14 and 15 involved gold-plated balls, barium-plated races, and S-Inconel retainers. Here again the initial radial play (0.0005 to 0.0006 in.) was maintained in one specimen and lost completely in the other in both tests. Retainer debris was evident in the bearings which failed, but not in those with internal clearance remaining—in one of the latter bearings a band of gold was found in each of the retainer ball pockets.

No visible gold remained on any of the balls in any case—it transferred to both the raceways and the retainers. The bearings ran well as long as some gold remained on the balls, but afterwards sliding contact between the unprotected balls and the S-Inconel retainer generated an abrasive debris which rapidly caused failure as gold and S-Inconel particles built up in the raceways.

Figure 5 shows the improved performance of this type of bearing in tests 16, 17, 18, and 19, where the silver-plated Circle C retainer was used. These bearings also had initial radial play levels of 0.0005 to 0.0006 in. and in three of the four tests this was maintained in one bearing and lost in the other. In the other test no measurable radial play remained in either specimen.

Heavy wear took place on the balls and races in all of these tests, but the retainers were relatively unaffected. Considerable amounts of gold transferred to the retainer ball pockets, providing effective sliding lubrication. These bearings ran well as long as enough protective barium remained on the raceways, but eventually, areas of exposed base metal picked up silver or came in contact with other base metal, leading to adhesive wear. Failure was caused by an irregular accumulation of wear debris and silver on the balls and raceways.

The fact that the initial radial play remained in some of the bearings again indicates that failure came shortly after this process began. This characteristic performance of the metallic film lubricated bearings means that catastrophic failure can come without much warning.

Tests 20, 21, 22, and 23 involved bearings with gold-plated balls, silver-plated races S-Inconel retainers, and 0.0003 to 0.0005 in. initial radial play. Figure 5 shows the wide variation in running times which was experienced.

In the case of the two shorter runs (20 and 79 hr) failure was obviously due to an accumulation of gold on the raceways which eliminated internal clearance, and the retainers were unaffected. No visible gold remained on the balls. In the longer runs (380 and 560 hr) raceway build-ups also caused seizure, but much of the accumulated debris was due to retainer wear. These were not long, smooth runs. Some large speed fluctuations, indicating periods of high running torque, were observed—particularly in the early stages of the tests.

Apparently a large amount of gold transfer, primarily from the balls to the races, took place early in each of these tests, making the bearings rough. In two cases, this roughness was enough to cause early failure. In tests 21 and 23 the initial high torque period was survived, perhaps because of the generation of abrasive retainer wear particles which ground away some of the build-up. Eventually however retainer debris itself accumulated enough to cause failure.

It is perhaps significant that the two bearings of this group with the smallest initial radial play (0.0003 in.) were involved in the two short runs. The slightly greater internal clearance in the other bearings may account for their survival of the early period of rough operation.

Two very long runs and one short one were experienced when the silver-plated Circle C retainer was used in conjunction with this basic bearing in tests 24, 25, and 26. All of these bearings had 0.0004 or 0.0005 in. initial radial play. The early failure (41 hr) was caused by silver flaking in the raceway, again pointing out the reliability problem with this type of lubrication. The bearings were running smoothly, but failure came suddenly and almost instantaneously. In the longer runs (1307 and 757 hr) a dip in speed again indicated considerable early gold transfer to the raceways, but here transfer to the retainer ball pockets was also taking place so that the raceway build-up was limited.

The natural migration of gold during the operation of this bearing configuration resulted in very effective metallic film lubrication. The retainer ball pockets were well protected, resulting in very little wear, and raceway build-up was not excessive. Eventual failure seemed to be the result of one or a combination of the following: Minor flaking in the retainer ball pockets after many hours of sliding contact with the balls; some Circle C debris from the edges of the retainer; raceway flaking due to work-hardening of the plating. Here again the actual failure process must have been rapid since one bearing in each case had good radial play remaining when autopsied.

Bearings similar to those of the two previous groups, but with an alternate plating source were also run. In tests 27 and 28 the S-Inconel retainer was used and two short runs resulted (see Figure 5). These failures were caused by a transfer of silver from the races to the balls of one bearing in each case. In the other specimen, the usual gold-to-silver transfer took place. With the "LR" gold and silver plating, the previously observed strong tendency for gold migration to silver-plated surfaces was not present. The reason for this basic difference in the platings produced by the two sources will be a very important item in Phase III testing. Since metallic build-up on the balls is more serious than raceway accumulation, in the cases where silver transferred to the gold, running time was short.

Tests 29, 30, and 31 involved the same ball and raceway platings and the silver-plated Circle C retainer. An early failure (63 hr) resulted from silver build-up on the balls similar to that described above, but two very long runs were attained with this configuration. The longest run of the entire program (2404 hr) left one pair of bearings severely damaged, so that one can only speculate that gold-to-silver transfer took place, forming a beneficial lubricating film on the contact elements and permitting a long life.

Test 31 involved only one bearing of this type and it was not the cause of the failure after 518 hr. It had radial play levels of 0.0007 in. before test and 0.0004 in. when autopsied. None of the original plating was visible on the balls or raceways and a powdery debris was prevalent, but the retainer ball pockets seem to be well protected and showed little wear.

Tests 32, 33, 34, and 35 involved silver-plated balls, barium-plated races, and S-Inconel retainers. The initial radial play of each of these bearings was either 0.0004 or 0.0005 in. These bearings ran well as long as barium remained on the raceways, but whenever base metal was exposed areas of silver build-up began. Silver also accumulated in the retainer pockets providing protection, but after a time the deposits there began to flake, and in one case (test 34) a loosened flake caused seizure of a bearing.

This configuration provided fairly good performance (lifetimes of 100 to 700 hr) but does not seem to offer as much promise as other types. Original radial play levels were maintained in some of the bearings, again indicating that the failure process was rapid once base metal was exposed to the silver.

When the silver-plated Circle C retainer was used, in tests 36, 37, and 38, similar running times were experienced (Figure 6). Two of the three failures here were traced to areas of silver build-up on the raceways, and the third was caused by a silver flake from a retainer ball pocket similar to that described above. All visible silver was lost from the balls in each of these tests, much of it forming flaking deposits in the retainer pockets. Even if raceway build-up could be prevented completely with this configuration, loose flakes would eventually cause catastrophic failure.

Tests 39, 40, and 41 involved silver-plated balls, gold-plated races, S-Inconel retainers, and initial radial play levels of 0.00025 to 0.0004 in. One very rapid failure (test 41) occurred because of excessive flaking of the silver plate on the balls, again demonstrating the reliability problem. In the other cases, the bearings ran for 100 and 189 hr before a gold and retainer wear debris build-up on the balls eliminated radial play. Since retainer wear debris was generated the running time was probably lengthened by a grinding away of some of the gold build-up. All gold was removed from both raceways during these tests, and no measurable radial play remained in any when autopsied.

Finally, tests 42, 43, 44, and 45 involved silver-plated balls, gold-plated races, and silver-plated Circle C retainers. The bearings had initial radial play of 0.0002 to 0.0004 in. and their performance was uniformly poor (Figure 6). Here gold built up rapidly on the balls, and to some extent in the retainer ball pockets. No retainer debris was generated so the gold build-up quickly caused failure. The same strong tendency for gold migration to silver-plated surfaces, which previously resulted in some long runs, quickly led to seizure with this configuration.

CONCLUDING REMARKS

The only Phase II type of bearing worthy of further consideration in the bearing program is that involving silver-plated races, gold-plated balls, and a silver-plated Circle "C" retainer. It will join two Phase I bearing configurations* which provided comparable performance as the basic Phase III bearing types. Since the relative merits of plating sources D and LR have not been settled experimentally, both will again be employed in early Phase III testing. Table 2 shows the bearing configurations still under consideration.

Table 2

Phase III Bearing Configurations.

Retainer	Ball Plating	Race Plating	Plating Source
Silver-plated fully machined Circle C	Gold	Gold	D and LR
None (full complement)	Gold	Gold	D and LR
Silver-plated fully machined Circle C	Gold	Silver	D and LR

Among the aims in Phase III will be reliability improvement by the control of plate adhesion, and the precision measurement and control of plating thickness. Phase III will involve several changes in the test procedure. To broaden the scope of the program, a radial load on the bearings will be introduced, and the test speed will be reduced to 1800 rpm. A magnetic coupling drive will be used to eliminate the drive motor from the vacuum chamber and permit lower ambient pressures. The bearings will run at synchronous speed until they reach a fixed torque level.

(Manuscript received December 4, 1963)

*1. Gold-plated balls and races and a silver-plated Circle C fully machined retainer.
2. Gold-plated balls and races, full complement (no retainer).

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