AEROSPACE INFORMATION REPORT

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LONG-TERM STORAGE OF MISSILE HYDRAULIC SYSTEMS

1. PURPOSE

Queries are not easily answered as to how long a missile hydraulic system may be inoperatively stored without affecting its final performance. This Aerospace Information Report summarizes the pertinent results of hydraulic system practices leading to greater storability.

2. SCOPE

Much of the available long-term storage test data has been reviewed and topically separated to enable the independent discussion of storage effects on fluids, seals, hydraulic components, and hydraulic systems. Comments are made in Section 4 concerning the applicability of the test results and regarding design practices for storability. Conclusions are drawn in Section 5 regarding inactive storage of hydraulic systems for at least a 5 year period.

3. TEST RESULTS AND EVALUATIONS

An interest in the length of time a missile hydraulic system can be stored was officially initiated by the USAF on the Minuteman Program in about 1957. One result of this interest was increased activity by various companies to evaluate the storage capabilities of other hydraulic systems and components.

3.1 Storage Of Hydraulic Fluids - Hydraulic fluid long-term storage data are confined to information resulting from storage of MIL-H-5606A fluid samples and samples of fluid having the same petroleum base as MIL-H-5606A. This fluid is used in many aircraft and missile hydraulic systems and has been termed the standard "red oil" for a number of years. Storage tests were performed to evaluate conditions under which contaminants are precipitated in the fluid and to determine the source of the contaminants and how they might be controlled.

An analysis of the test results shows that though contaminants may agglomerate in fluids being stored, redistribution usually occurs by agitation of system operation. In addition the needle-like particles formed in MIL-H-5606A, due to conditions associated with the viscosity improver additive, will disappear by heating or system operation. Because fluid samples stored for as long as 17 years have shown no significant deviation from the original fluid specification, contamination control appears to be the only improvement needed when considering the ability to store fluids for long periods. The contamination control needed involves making sure the fluid is as clean as possible at the initiation of storage. Sampling during the storage period to evaluate contamination level is not advisable since agglomerated particles, or false readings from the needle-like particles, may indicate a contamination problem that really does not exist. System operation during the storage period does not appear to be an advisable practice, as such operation will generate contaminant particles, which when present, may result in a condition more severe than agglomeration.

The summary results of some of the more important documented fluid storage tests follow. Other references to storage effects related to fluids will be found in the discussion on seals, components and systems.

3.1.1 Summary of Reference 1 Fluid Data - Storage data from seven sources, including two fluid manufacturers, indicated no changes in properties of MIL-H-5606A (some MIL-O-5606 also) over long time periods, provided that the surfaces in contact with the fluid are not in contact with air. There is no reason why fluid, suitably formulated and kept in a clean, closed system, cannot remain usable for three years or possibly longer.

3.1.2 Summary of Data from Reference 13 - Five-gallon samples were periodically removed from a stored 55-gallon drum of MIL-H-5606A over a period of more than six years. Ambient air filled the space voided by the sampling. Analysis of the samples showed no significant change in fluid properties.

3.1.3 Summary of Data from References 9 and 13 - During a three-year fluid-seal-component test program samples of fluids placed in tin plate cans, glass bottles, and polyethylene bags were evaluated at four month intervals. The bags were leached, dissolved, or both by MIL-H-5606A; other containers showed no interaction.

3.1.4 Summary of Reference 12 Fluid Data - There was no conclusive evidence that the viscosity improver additive produces deposits in normal system operation. Particle agglomeration occurred after three months storage of a 100 ml fluid sample to which was added 0.3 mg AC dust. The sample was pressurized with nitrogen during the storage period.

3.1.5 Summary of Reference 14 Fluid Data - The agglomeration of particles evidenced after fluid storage for long periods may be dispersed by agitation, but will recur by renewed storage. Particle growth can be synthetically induced in MIL-H-5606A fluid by addition of contaminants. This cannot, however, be accomplished in fluids containing polar rust preventive agents or in fluids that do not contain methacrylate viscosity-temperature improvers. The precipitate may be controlled by minimizing the original contaminant.

3.1.6 Summary of Reference 8 Fluid Data - The contamination associated with stored hydraulic fluid appears to be conclusively related to viscosity improvers in the fluid. This conclusion resulted from tests showing that heating MIL-H-5606A to 350 F for 2 minutes after a 180 F soak reduced the silting index considerably and in addition dissolved the needle-like crystals that form in the fluid under certain circumstances.

3.1.7 Summary of Data from References 5 and 13 - The disassembly of hydraulic parts showed no evidence of corrosion following storage for 18 months of a F4U-4 aircraft with MIL-O-5606 retained in the system. It was concluded that MIL-O-5606 did not need to be replaced by preservative fluid prior to storage.

3.1.8 Summary of Data from References 2, 6 and 13 - Fluid samples were removed from the B-24 "Lady Be Good" aircraft after 17 years in the Libyan Desert. The AN-VV-O-366 fluid met the original specification.

3.2 Storage Effects On Seals And Seal Materials - The greater majority of the data available from the evaluation of seals for long-term storage has been provided from shelf aging tests of elastomers. Data have been reported from tests where seals were: individually packaged, loose in closed cardboard containers, or in polyethylene bags. Uninstalled elastomers suffer no serious degradation, at least for periods of 6 to 8 years, regardless of whether they were stored in open containers or sealed. Oven aging at increased temperatures proved to be a reasonable procedure to obtain accelerated aging though the estimate of the equivalent natural age varied between 10/1 and 30/1 for 160 F aging to 70/1 for 186 F aging.

Swell tests with Buna N and Viton A after three years showed both materials were acceptable but that beyond three years the Buna N was somewhat more satisfactory than Viton A.

The data from the aging and swell tests do not provide conclusive evidence that seals are adequate in component installations. However, an indication of the adequacy of seals in the installed condition has been shown by some storage tests on linear actuators. Actuators incorporating O-rings of various materials were stored to evaluate seal deterioration that would lead to leakage and material cold flow that would lead to stiction. It was concluded that seal deterioration was not a serious problem since leakage was observed in only a few random cases.

The comparison of the breakaway friction before and after 14 years storage indicated some variation. One set of data showed the range of breakaway friction as 5 to 35 lb for the actuators prior to storage and 7 to 28 lb after storage. From these data it must be concluded that no definite pattern was established that showed evidence of seal material cold flow (compression set) resulting in increased breakaway friction following long-term storage. Another set of data showed the worst condition of change in breakaway force as 13 to 72 lb. This change on a percentage basis is great, but from a force magnitude basis is usually insignificant in a 3000 psi hydraulic system for a typical missile application. However there have been recent applications where single-stage (low pressure gain) servovalves and small area actuators are employed. A large friction increase in these applications may be intolerable. The other major point is that the increased breakaway friction would only be encountered on the initial stroke of the actuator following long-term storage. Normal operating breakaway friction values would be encountered in subsequent strokes.

Based on the percentage increase in average force, from the above data, a testing agency's recommendation was that breakaway friction needed to be reduced and that an interim solution would be to exercise hydraulic systems during storage. Since this conclusion was not formulated using all of the facts, i.e., breakaway force versus total available force, it should be considered invalid. Furthermore the permanent solution to decreasing stiction is by redesign of the seal gland, which design should be thoroughly evaluated prior to recommending the expensive program of requiring system exercising during storage.

There appears to be no justified cause to doubt the ability to store elastomeric seals, either installed or loose, for periods in excess of 8 years. The summary of results of some of the more important documented seal storage tests follows.

Other references to storage effects on seals will be found in the discussion on components and systems. Section 6.3 contains a reference list of material on seal shelf aging that became available too late to be incorporated in this report.

3.2.1 Summary of Reference 13 Seal Data - Several independent evaluations have led to the conclusion that elastomers stored outside of components apparently suffer no serious degradation, regardless of whether they are stored in open containers or sealed, at least for periods of 6 to 8 years. The worst variation in seal properties of Buna N O-rings after a four year shelf aging test was as follows:

a. The change in tensile strength was + 14% from 1510 psi
b. The change in elongation was -22% from 226%
c. The change in modulus at 100% elongation was + 37% from 440 psi
d. The change in Shore A hardness was $+8^{\circ}$ from 69°.

Other tests were performed for shorter than three year durations, and on other materials with results consistent with the above data.

In other evaluations, O-rings, which had reached the maximum allowable storage age of four years under MIL-P-5516, were tested for an additional four years of shelf aging. During this additional storage all seals were not kept individually packaged. At the conclusion of this added four years the maximum changes in properties resulting from the additional four years of aging were:

a. A reduction in tensile strength from 1730 to 1640 psi (-5%).
b. An increase in ultimate elongation from 150 to 160%.
c. A reduction in modulus at 100% elongation from 980 to 850 psi.
d. A reduction in permanent set at 50% elongation from 2 to 1%.
e. An increase in specific gravity from 1.31 to 1.33.

From the results of this test it was concluded that O-rings originally meeting MIL-P-5516 will be satisfactory for service after shelf aging at moderate temperatures for at least 8 years.

<u>Comment</u> - Test data obtained from the Mare Island Naval Shipyard shows that the tensile strength of seals procured under MIL-P-5516 increases with storage time to a value of +36% at 10 years.

There are no known existing specifications for acceptance of seals following storage. This suggests that engineering judgment based on experience is used to establish the adequacy of seal properties following storage. Observation of the data for the 0-4 year and 0-6 year shelf aging tests with the data from the fourth and eighth years shows that the properties, with the exception of tensile strength, tend to change only by a small amount after the fourth year. The amount of change in tensile strength recorded during tests does not appear to be deleterious to seal use. These observations therefore confirm that seals stored outside components are good for at least eight years and probably more than ten.

3.2.2 <u>Summary of Reference 10 Seal Data</u> - A three year seal immersion test showed that none of the rubbers tested were degraded beyond usefulness. The tested compounds were Viton A, Silicone LS53, Buna N, and Neoprene W; all tested per procedures contained in MIL-P-25732A. The ASTM D471-57T volume swell test at 160 F was judged a reasonably accurate accelerated aging test. The oven aging decreased the aging time by 10/1 or 30/1 depending on the process.

<u>Comments</u> - The most important result of the swell test was considered the fact that after reaching maximum swell, due to fluid absorption, continued immersion causes the extraction of a portion of the plasticizer (present in Buna N and Neoprene compounds) and a resultant reduction in swell.

3.2.3 <u>Summary of Reference 9 Seal Data</u> - Viton A, Buna N, and Neoprene W seals were tested in a three year basic volume swell test and showed that Viton A and Buna N were acceptable. Beyond three years Viton A appeared to degrade more rapidly than Buna N.

Four sets of 5 World War II aircraft servo cylinders were stored for three years. Each cylinder contained a combination of new or aged Buna N seals in the piston and gland installations. The actuators were stored either filled or flushed and drained. This preparation provided eight separate test configurations. Results of the test were: (1) the tensile modulus of piston seals was greater than that of shaft seals; (2) seals in actuators without fluid had a lower modulus than seals in filled actuators; and (3) aged seals, those already installed five years prior to the test, had a greater modulus than new seals. These results show that an increased modulus means increased age and that the presence of MIL-H-5606A is the major cause of aging. Of the three seal failures, two were in cylinders filled with the fluid. This agrees with the conclusion that fluid ages seals. All of the seal failures were of old rings indicating a useful storage life in excess of eight years.

An evaluation of seal breakaway friction during one half and one year storage periods was performed using 108 aircraft servo cylinders. The cylinders were equipped with either Viton A, aged AN Buna N, MS Buna N, Neoprene W, AN Buna N, or Fluorosilicone seals. In almost all cases the breakaway friction increased as a result of storage. The MS Buna N seals were superior showing an average increase from 20 to 24 lb in the one half year test and from 17 to 28 lb in the one year test. Comparison of the results of the one half year test to those of the one year test indicated the majority of the increase developed during the first six months. Observation of the worst case for a single actuator showed an increased friction from 13 to 72 lb.

Comments - The poorer results with Viton after three years oil immersion are probably due to a higher equilibrium value for volume change, due to the fact that Viton compounds generally contain no extractable plasticizer.

The statement that "the presence of MIL-H-5606A is the major cause of aging" is debatable. Assuming a Buna N compound compatible with MIL-H-5606A (i.e. - one which has a small positive swell in this fluid) the fluid would serve to protect the seals from the two of the three generally recognized causes of aging - 1) continued vulcanization - that is, continued chemical activity of the unused residue of vulcanization ingredients in the compound, 2) oxidation and 3) volatilization of plasticizer. The fluid would not protect from 1) above, of course. Also, there may be some loss of plasticizer, but in a compatible fluid/seal system this is really an exchange of fluid for plasticizer.

The conclusion "a useful life in excess of 8 years" was made by the author of Reference 9 and does not appear to be supported by test results.

The increase from 13 to 72 lb would have negligible effect on many 3000 psi missile hydraulic systems. Lately, however, there have been applications where single stage servovalves and small actuators are employed. Such an increase could not be tolerated in these applications. It must also be recognized that the World War II actuators were built to a state-of-the-art technology much lower than the missile technology of today.

3.2.4 Summary of Reference 1 Seal Data - Storage tests were conducted to evaluate deterioration of seals leading to leakage, and cold flow (compression set) of seals leading to stiction. The objective was accomplished using 147 World War II servo cylinders stored for 14 years. The actuators contained AN6227-23 and AN6227-19 O-rings. The test results identified four internal leaks and no external leaks. The average breakaway friction after storage was 16.4 lb before cycling and 12 lb after cycling. The range of breakaway friction for all of the actuators after storage was 7 to 28 lb as compared to a before storage range of 5 to 35 lb. The average breakaway friction increased 30% while the maximum friction reduced 20% during the 14 years. The testing agency concluded that deterioration of seals was not a serious problem and that the cold flow (compression set) of seals resulting in stiction needed some attention. Missile storage for three years was justified by careful selection of the servo design and seals. An interim solution to stiction was suggested as required exercising of the hydraulic system during storage.

Comments - The data showing the change in stiction (breakaway friction) resulting from 14 years storage do not consistently show increased breakaway. Because of this it must be assumed that some seal configurations provide leakage control without resulting in increased breakaway friction with time. Since this has been achieved, even though it was not intentional, it must be concluded that design practices can be developed which will provide the same results more consistently. The investigation of design improvements should be explored thoroughly prior to recommending the costly procedure of exercising during storage as suggested by the testing agency.

3.3 Component Performance Resulting From Storage - Long-term storage data on hydraulic system components have been collected for intentionally shelf stored components, equipment installed in missiles and aircraft that have been intentionally stored, and equipment recovered from World War II aircraft that had crash landed and remained lost for many years. The data of particular interest was on hydraulic servovalves, actuators, pumps, and accumulators.

A few servovalves having two to three years of service life were tested following an additional two to three years of storage without exercising, and they showed no performance deterioration. This was true even though the fluid had drained from the hydraulic system due to faulty capping procedures. These data are contrasted to data obtained by testing servovalves that had been partially filled with fluid which resulted in the valves not operating after two years of storage. Storage results such as this emphasize the inconsistency in performance of servovalves which are stored partially filled. The risk associated with storing a partially filled hydraulic system is not justified and as a general practice should be avoided.

Performance tests were conducted on three servovalves before and after storage for two to three years. Two of these valves were of the Moog Model 902E wet torque motor type and one was a Moog Model 2054B dry torque motor type. The performance tests showed no significant differences in the before and after performance. The data comparing 46 shelf stored servovalves to 71 similar valves installed in missiles that were periodically exercised showed no performance differences after approximately four years of storage.

It can be concluded that by using proper storage procedure hydraulic servovalves should be expected to operate per their performance specifications after at least four years of unexercised storage, and in many cases after longer storage durations.

Information to be learned from the storage of linear actuators is primarily related to the evaluation of seals during storage. This has already been discussed in Section 3.2. Particular information related to the actuator itself indicated that piston rods moved freely and there was no corrosion of parts after 17 years inactive storage on the Libyan Desert. Other actuator component test data resulted from tests where obtaining particular seal information was not the test objective.

The data available allow comparison of storage results where there was no exercising, to storage with infrequent exercising, and with frequent exercising. The data support the fact that frequent exercising causes wear in components and such wear increases the probability of failure. Such failures are not attributable to storage. The comparison of 46 shelf stored actuators to 71 actuators stored in missiles that were infrequently exercised revealed no failures in either case. This supports the conclusion that actuators, when properly designed can be stored continuously inactive at least three years and possibly up to 10 years (as a limiting value for seals) without affecting performance significantly.

Pump storage data reflect the same conclusion as that made above with respect to actuators. Frequent exercising reduces the storage life of a component. Without exercising, the pump in the "Lady Be Good" aircraft, after 17 years of inactivity, passed its original procurement specification. The satisfactory performance of this particular unit after very long storage can be attributed to the short aircraft service history of approximately 125 hr. In the case of missiles, shorter service life might well be expected since the missiles are normally stored following a minimum of operating time.

Motor pump packages from the Polaris program showed no performance change after three years of fleet service where they were exercised once per month. Similarly the hydraulic pumps from the Atlas program have demonstrated an average discrepancy rate less than 1/20 of one percent of units in the field with approximately one per month operation.

The possible loss of air precharge from hydraulic accumulators is a problem not experienced by other components in a hydraulic system. The natural porosity of elastomeric materials results in a slight leakage of "seepage" of high pressure gas through or past the O-rings, or through the bladder or diaphragm of hydraulic accumulators. Therefore, some air leakage should be allowed without defining the condition as a storage failure. The amount of allowable leakage depends on the particular system design and its established performance requirements.

Accumulator storage tests, with both piston and bladder accumulators, have all shown that some leakage will occur, although in most cases the resultant pressure drop has been insignificant. Twenty-three piston accumulators of various sizes were stored for a minimum of three years in an outdoor environment. The leakage averaged 1% for all 23 actuators and a maximum of 12%, or 90 psi, for the worst single case.

An installed bladder accumulator in a B-17 for 23 years on the Greenland Ice Cap was found to have only a 25 psi drop in the original charging pressure of 350 psi. The majority of the bladder accumulators inspected after storage had broken bladders. In almost all cases the bladder ruptures were the result of an improper design practice and not attributable to storage. Because of these design deficiencies, it is concluded that the remainder of the accumulators tested, for which failure details were not available, failed in a similar manner. The average precharge leakage rate for piston type accumulators stored so that leakage could be periodically measured was 0.3% per year of storage.

During three and one-half years of field experience with approximately 1500 accessory power units delivered to Minuteman program no external leakage of pump shaft seal or static O-rings has been observed. The overall results of the component storage tests tend to indicate that there should be no difficulty in inactively storing missile hydraulic system components for at least five years when up-to-date design practices are utilized. Though the available pump data support his conclusion, additional pump storage testing would provide a larger data sample from which more accurate conclusions could be drawn, particularly in respect to pump shaft dynamic seals.

The summary results of some of the more important documented component storage tests follow. Other references to storage effects related to components will be found in the discussion on seals and systems.

3.3.1 Summary of Reference 5 Component Data - Three Weston servovalves were tested after two to five years of installed storage in a stored F9F-8 jet aircraft. During the storage period all of the preservative fluid had drained from the aircraft system. Considerable service life of aircraft was indicated. The test results showed no deterioration of performance due to prior service or storage totaling six years, nine months for each of two valves and eight years, six months for the third valve.

3.3.2 Summary of Reference 3 Component Data - Six units each of double shell accumulators having capacities of 25, 50, and 200 cu in. were stored with five lightweight 25 cu in. units for a minimum of three years following an initial 750 psig nitrogen precharge. Accumulator breakaway friction was periodically checked. Pressure and temperature of each unit were monitored each week. No evidence of seizing of seals was observed. Leakage averaged less than 1% for all accumulators with the worst leakage case being 12% of 90 psi.

3.3.3 Summary of Data from Reference 11 - The recovery of items from a B-17 aircraft, which crash landed in 1942 in good condition on the Greenland Ice Cap, was accomplished in 1965. Included in the recovered items were fluid samples, a hydraulic turret transmission, a cowl flap cylinder, an engine driven pump, spherical accumulator (with rubber diaphragm) hoses and rubber samples. Component evaluation has not been completed; however, preliminary tests have shown the equipment to be very serviceable. The accumulator air pressure was 325 psi after recovery indicating a loss of 25-50 psi during the 23-year period.

3.3.4 Summary of Data from Reference 6 and 2 - A number of hydraulic components were removed from a B24-D aircraft which had remained in good condition for 17 years on the Libyan Desert following a crash landing. The aircraft had been in service for approximately 125 operating hours. The components were a main system pump, hydraulic motor, relief valve, unloading valve, accumulator, turret transmission, filter and various cylinders. The motor, right main gear cylinder, swivel joint, relief valve, check valve, turret valve assembly, gun charger, nose gear cylinder, and another actuating cylinder were disassembled and inspected. The pump, left flap cylinder, swivel joint, relief valve, check valve, accumulator, and small cylinder were tested in the "as recovered" condition.

Exterior inspection of components showed little or no corrosion, piston rods moved freely, were coated with oil when extended, and were shiny in appearance. Drive shafts rotated freely by hand and bearings were good. The pump was tested to the original production test and met the delivery requirements of a new unit. Both the interior and exterior of the motor were exposed to sand during the crash. The drive shaft, however, turned freely by hand and there was no internal corrosion or deterioration. The motor pump pressure test showed acceptable performance and the motor had normal cylinder block lift, volumetric efficiency, and differential pressure. Leakage was above normal due to sand scoring. The scoring was determined to be caused by large amounts of sand injestion during ground service. Sand injestion was so severe that 14 aircraft on the same mission had to turn back due to sand in the engines.

3.3.5 Summary of Reference 13 Component Data

3.3.5.1 Pumps - A relatively low failure rate appears to be applicable to hydraulic pumps in dormant situations. Exercising at period intervals is an important factor. Leakage is the primary mode of failure.

Pump storage data consist of the results of storage of a large number of units for six months to three years with exercising at 90-day intervals. Comparisons are made to storage of a small number of units for 10 years with exercising once per week for nine years and once per two weeks for the final year. The data also shows the results of storage of two units for 17 years without exercising.

Analysis of these results show more failures for the highly exercised equipment than was experienced for the 90-day exercising and no failures after storage for the units that were not exercised. Where failure times during storage were available, which was for the three-year tests, the failures were evidenced predominately at the end of the three years.

Comments - The practice of exercising a system to determine whether it is in satisfactory operating condition is a reliability test, not a test of the capability of the system to be stored Repeated exercising wears out parts and failures resulting from such wear should not be attributed to a result of storage. The above data tend to amplify this comment.

3.3.5.2 Actuators - Note: The results of actuator storage tests included inactive shelf storage data and data for exercised equipment in system installations. Some of the data utilized in this reference for actuator component discussion will be discussed as system data later in this report. Other data discussed in this reference as actuator component data were primarily the result of seal storage testing which has already been discussed. These data are not summarized here.

Actuators suffer serious degradation if they are not exercised during storage. Failure rates for unexercised actuators are on the order of 50 times higher than for exercised actuators. If properly designed and exercised, actuator failure rates can be maintained at a reasonably low level in storage conditions.

The actuator storage data compare five parts stored for 17 years without exercising with 90 parts, some stored for a maximum of three years, having little exercising and 11 parts stored in excess of 10 years with frequent exercising. The data also compares 117 parts, some having a maximum of 46-month storage, where 40% were inactively shelf stored and 60% were periodically exercised in missile systems.

There were no failures of the five aircraft servocylinders stored for 17 years or the 117 missile actuators of which 40% were shelf stored. Eight of the eleven actuators frequently exercised failed during the 10 years of storage. Of the 90 parts stored from 1 to 3 years, five leakage failures were observed in comparison to 38 other failure conditions for the actuator. Based on these data samples and the others mentioned in the above comment, failure rates were calculated.

Comment - The excessive number of failures within the sample of 90 parts indicates a poor actuator design or an actuator where development had not been completed. This type data should not be used to show storage capability because the parts should be expected to fail from other causes. The eight failures within the field of 11 actuators frequently exercised emphasizes the comment made previously that exercise produces wear leading to component failure. The most significant data from this reference is that no distinction in performance after storage could be made between actuators that were shelf stored and actuators periodically exercised in missiles. It can be concluded from this that exercising is not necessary to ensure operational capability of actuators after at least three years storage and possibly much longer.

3.3.5.3 Servovalves - Servovalves, like actuators, do not suffer particularly from dormancy provided they are properly designed and periodically exercised. In general, their failure rate does not change significantly with time under these conditions.

An F9F-8 aircraft with three servovalves was stored for 2.5 years. MIL-H-6083 preservative fluid was lost during the storage period through improper capping. The valves operated adequately after the storage period. Each of the 117 actuators mentioned in the previous discussion were fitted with a servovalve. Fluid in these systems was MIL-H-25598. All of the valves, whether periodically exercised in a missile or shelf stored, successfully passed performance tests after storage. Similar 2520 valves from 630 missiles showed no failure during six months to two years storage with periodic exercising of the missiles.

Comment - The servovalve storage data indicate acceptable storage for at least three years because valves stored without exercising were as acceptable as those that were exercised. It is, therefore, concluded that exercising does not appear to be required.

3.3.5.4 Solenoid Valves - Forty-six hydraulic solenoid valves all failed to operate after five years of shelf storage prior to customer delivery. Failures were attributed to fluid causing sticky sliders, but cleaning did not relieve the stickiness.

Comment - The data presented for the 46 solenoid valves do not appear to be a valid storage test. There is no data to indicate the valves operated successfully before storage. Acceptable operation before storage is further questioned by the fact that valve cleaning did not cure the stickiness. Cleaning would have cured the stickiness if the fluid were responsible.

3.3.5.5 Accumulators - Diaphragm and bladder-type accumulators exhibit relatively high storage related failure rates. Failure rates for the diaphragm, bladder, and piston types of accumulators could be reduced considerably by better design and closer control over gas charging and hydraulic fluid filling procedures. With present designs, accumulators are not recommended for use in systems that are to experience long dormant periods. A better choice is the use of boot-strap type reservoir with mechanical pressurization.

Six hundred 3 to 5-inch diameter piston accumulators stored on the shelf for two years without fluid and the pistons bottomed, all leaked when tested. Thirteen of thirty missile accumulators stored in the missiles from one to three years failed. A number of these failures were attributed to shipment. The missiles were not regularly exercised. Eleven bladder accumulators on 30 missile trailers, stored for one to three years, were found ruptured. The causes of failure were all a function of improper design which allowed overstressing or scratching of the bladder. Five percent of the bladder accumulators in 26 B-26 aircraft reactivated after two years storage had to be replaced. The bladder accumulator in a crashed B-24 was recovered after 17 years. The deformation of the bladder indicated the air charge held for a number of years prior to rupture of the bladder. Reservoirs on the 26 B-26 aircraft which were reactivated after two years storage satisfied aircraft requirements.

Comments - During storage, some leakage of air from an accumulator is to be expected. As long as that leakage is not sufficient to affect the required performance of the system, no failure should be considered to have occurred. Measurement of precharge pressure to determine air leakage is convenient, but must be done at the same temperature each time. A false indication of leakage can be obtained if the air precharge of the accumulator is introduced by other than an isothermal process.

The piston accumulators tested include dynamic piston seal installations and static seal installations similar to those in linear actuators discussed in Section 3.2.4. The design of the actuator seal installations showed that sealing during long-term storage can be achieved and should be as adaptable for the accumulator liquid seal designs as it is for actuator design.

The storage data for bladder accumulators indicates that by proper design practice these accumulators can also be made to survive long-term storage. However, the use of piston instead of bladder accumulators is still considered the best design practice.

The statement that accumulators could better be replaced by boot-strap reservoirs in systems requiring long dormant storage is not an option that can be exercised by the designer. The purpose for the accumulator is to provide a capability for satisfying transient requirements in the system. This capability cannot be satisfied by a boot-strap reservoir.

3.3.6 Summary of Reference 2 Component Data - Fifteen hundred Minuteman integrated hydraulic power packages have been delivered over a 3-1/2 year period. Field experience with these packages has shown no evidence of external fluid leakage. Some internal dynamic shaft seal leakage was reported; however, this is not attributable to storage effects.

Two thousand Polaris motor pumps were delivered in a four year period with 500 having service life in excess of three years. These units when returned from fleet use were tested and the data compared to performance data obtained at the time of manufacture. No perceptible differences were indicated. The components had been exercised once per six months when stored outside the missile and once per month as part of the missile checkout in service.

Eighteen hundred Atlas hydraulic power unit pumps were delivered in an eight year period. Of these, 100 had a service life of 7-1/2 years, 500 had a life in excess of 5 years, and 1000 had a life in excess of 3 years. The pumps were exercised during missile fill and bleed procedures for 30 seconds approximately once per month. In addition, the pumps were operated 2 to 5 minutes per year during engine test. Problems encountered have been from leakage and have averaged less than 0.05 % of the units in the field.

3.4 Hydraulic System Storage Effects - Long-term storage test results for complete hydraulic systems are available for both aircraft and missile systems. Aircraft which were stored up to two years and subsequently inspected were found to have faulty hydraulic systems. The majority of discrepancies with the hydraulic systems could be attributed to improper preparation for storage. Other discrepancies were obvious weaknesses in the original system design. Such test results as these are not considered valuable to the study of long-term storage capability.

Field service storage of both Nike and Terrier missiles has provided data leading to hydraulic system design changes which have improved the storage life of these missiles. The redesigned systems have demonstrated no discrepancies attributable to storage over three-year periods. The experience gained by redesigning for improved storage is valuable in that it shows the advantage to be gained by initially designing systems for long-term storage life. These advantages are mainly in use of up-to-date seal configurations and component design with minimum leakage potential.

The storage of more than 5700 surface to air missiles for up to three years demonstrated that the number of hydraulic system discrepancies was near the 0.1% value and could be considered random. Random discrepancies result from faulty seal installations, faulty or damaged sealing surfaces, or such like. These conditions produce leakage as a function of operating time and not as a function of storage time.

Other published results of missile hydraulic system storage are for surface to surface missiles. One group of 157 missiles had leaks in more than 10% of the missiles removed from shelf storage during the first two weeks. These failures cannot be attributed to storage: more correctly they are a result of seal gland design or poor assembly practices. Another single missile that was stored two years without exercising had no hydraulic system discrepancies. This result demonstrates that missile hydraulic system storage is a practical design consideration.

The summary of results of some of the more important documented vehicle storage tests from which hydraulic system data is available follows.

3.4.1 Summary of Reference 1 System Data - A survey was made of 120 hydraulic system manufacturers and users regarding hydraulic problems related to three year storage of systems using MIL-H-5606A and similar base fluids. Forty replies were received containing useful information. In summary, six had problems with moisture in the fluid, three with air in the fluid, four with dirt in the fluid, three with fluid thickening with age, eleven with aging of elastomeric seals, five with stiction, and four had no problems.

Comment - All of the above mentioned problems have been discussed earlier in this report and were concluded not to be storage problems provided that precautions are taken in preparation for storage such that storage is not initiated with a contaminated system.

3.4.2 Summary of Data from Reference 5 - An F7U aircraft was stored for two years after considerable service life. After the storage period a flyaway inspection was performed. This inspection revealed 78 aircraft discrepancies, 31 of which were connected with the hydraulic system. One was considered attributable to preservation. Inspection of O-rings on the airframe indicated that these O-rings would have deteriorated even if the aircraft had been kept operational.

Comment - A number of the hydraulic discrepancies were attributed to such things as missing lockwire--this indicating that there was little aircraft preparation prior to storage. Without knowing that the hydraulic system was satisfactorily prepared for storage, the discrepancies evaluated in the flyaway inspection cannot be accepted as being the result of storage or even inferred that they occurred during the storage period.

3.4.3 Summary of Data from Reference 4 - A number of aircraft, B-26's and F-100's, were stored from one to two years with no special storage preparation, preservation, or maintenance during storage, except that the fluid was changed in some aircraft hydraulic systems prior to storage. Reactivation of the aircraft following storage required considerable replacement of components including 100% replacement of seals in fluid disconnects. Reasons for replacement are not specifically given although leakage may be implied. In many cases fluid needed replacement due to contamination. It was concluded that the information obtained could not be used as an accurate storage analysis, but was to be regarded only as general information.

Comment - The lack of thoroughly examining the aircraft prior to storage is emphasized by the author's remark: "If leakage was observed, it was stopped." This remark indicates that the cause of such leakage was not investigated and the replacements following the storage may have been required due to the inadequate maintenance of the system. The evidence of contamination is also typical of a system inadequately prepared for storage. Symptoms of this condition have already been discussed in earlier report sections. The 100% replacement of fluid disconnect seals indicates poor component design rather than seal storage inadequacy.

3.4.4 Summary of Reference 9 System Data - Eighteen months storage of a number of groups of Minuteman missile power system hardware showed no objectionable change in dynamic performance or prohibitive leakage attributable to storage. All systems were exercised, but each group was exercised at a different interval from the others.

3.4.5 Summary of Data from Reference 2 - Between 4000-5000 Nike power packages were delivered between 1956 and 1963. Of these, 2000 have more than five years service experience and 100 have more than seven years service. The units are exercised two hours per month as part of the operational missile checkout. The initial configuration of the system was powered by ethylene oxide fuel and 5% of the mentioned stored systems had ethylene oxide leaks. After two years service life, 2% of the systems reported on had dynamic seal leakage attributable to wear during operation periods. The advanced configuration of these packages incorporates an improved battery powered electric motor drive. Results of field service in excess of three years for 1000 units indicated that there were no problems except random isolated leakage discrepancies attributable to mishandling.

More than 7500 Terrier hydraulic control systems were delivered within a ten year period. Seven hundred of these units had seven to nine years field experience. Fifteen hundred had more than five years of life with 3500 more than three years life. No system was stored more than 6 months without a disassembly inspection. As part of a shipboard missile the system was functionally checked each 30 days for the first 36 months and then at 6-month intervals. When the missiles were removed from ships, the storage and disassembly cycle was repeated. Some of the above systems have had more than five cycles of this procedure.

Initial configurations of the Terrier hydraulic system exhibited some leakage of both pressurization gas and hydraulic fluid. The more recent configuration, using solid propellant to generate pressurization gas, has exhibited no system storage problems.

Comment - Experience with stored hydraulic systems has benefited both the Nike and Terrier programs in that the advanced configuration has incorporated design changes to improve the storability. The emphasis on storability as an initial design consideration should be given more attention than it has had in past programs. (See Section 4 for general suggestions on general design practices for storage.)

3.4.6 Summary of Reference 13 System Data - A survey of more than 5700 surface to air missiles, stored from six months up to three years, indicated a total of seven hydraulic leaks, five of which were at the end of three years of storage. More than 1100 missiles had two years storage without failure. The storage period included some time in a depot, where the missiles were exercised each 90 days, and some time in the field, where there was no exercising. The percentage of time in the field is unknown. A single surface to air missile, in addition to the above, was stored 38 months without exercising and exhibited no failures.

Comment - Without more explicit data on the exercising history of the above system it is difficult to evaluate the probable cause of the failures. These failures, however, were on less than 0.13% of the total number of missiles and may, therefore, be considered random discrepancies. A certain number of random discrepancies occur in each assembly process and result from such things as faulty O-rings or O-ring installations, damaged sealing surfaces or O-ring grooves, etc. Leakage as a result of random discrepancies is not a function of storage duration, but a function of system operating time.

A survey of 157 surface to surface missiles showed that more than 10% of those removed from storage in the first two weeks leaked. Over the first six week period an additional 10% leaked. All systems were removed from storage after 17 weeks. Two additional surface to surface missiles were stored for two-year periods. One was stored without exercising and had no failures. The other was stored and exercised each six-month period. Two leakage failures resulted.

Comment - The failure results from shelving the 157 missiles cannot be considered the result of storage. Poor design or improper installation would most adequately represent the reason for such a high failure rate over such a short time duration. The results of storage of the two additional missiles indicate storage capability for two years without exercising is safer than storage with exercising because there is no wear due to operation.

4. DESIGN PRACTICE FOR LONG-TERM STORAGE

A missile hydraulic system can be designed such that after five years of inactive storage the system will be operationally reliable if proper design criteria are initially employed. Some general criteria are listed below as a guide to designers. These criteria affect, to various degrees, the storability of a hydraulic system although some of the listed items may be thought to be more important to reliability aspects of the design.

The particular criteria applicable for a selected hardware configuration must be evaluated on the basis of the application. References 1 and 7 may also be of value in selecting applicable criteria. No attempt has been made to list criteria in the order of importance.

a. Keep the total number of linear inches of external seals, in particular dynamic seals, to a minimum.

b. Maintain slightly pressurized (5 to 75 psi) condition throughout the system during storage, if possible, to avoid entry of contaminants and to provide a positive inlet pressure for systems employing a hydraulic pump(s)

c. Bottled gas should only be used when the bottles can be isolated by burst discs, squib valves, etc., from the remainder of the system during storage.

d. Use a self-contained system, sealed and not requiring connection to ground check-out during the storage period.

e. Select a fluid acceptable for both the operation and storage temperature ranges and use only fluid additives that are essential.

f. Use a helium leak check prior to filling the system.

g. Eliminate reconnectable fluid fittings and use modular packaging techniques wherever possible.

h. Use wire mesh filters when onboard filtration is required.

i. Take adequate contamination precautions by carefully controlling manufacturing and assembly and preventing water, air, and solid particles from entering the fluid prior to and during filling.

j. Know the storability characteristics of the materials in the system.

5. CONCLUSIONS

The ability to store a missile inactively for as long as five years prior to its operational use has to some degree been considered impractical because "a hydraulic system cannot be stored for five years." This conclusion has been based on assumption rather than fact. Data to "support" the above conclusion has been taken from the same reference material mentioned throughout this report. A closer examination of this data reveals the fallacy in assuming that all failures that occur during a storage period are the result of storage. Most generally the failures attributed to storage resulted from exercising the system (wear out) or were due to the initial conditions where storage preparation was not provided. Unknown operational history of components prior to storage and lack of the advantage of advancements made in technology during the storage period were also factors. The storability picture is made even more negative by assuming a theoretical failure at the end of a test, even if none occurred, in order to establish a failure rate.

Storage tests, performed to date, have not included the inactive five year storage of the hydraulic system of a functional missile. Shorter duration hydraulic system storage tests have shown, that with adequate preparation prior to storage, no problems attributable to storage will be encountered. Tests of longer duration than five years, using components typical of those in missile hydraulic systems, leave no doubt that such components may be stored for five years without affecting performance. The proof is more conclusive for components in nearly new condition, which would be the case for missile components in storage, as compared to aircraft components which have a long service life prior to deactivation or storage.

The storage of seals and fluid for as long as five years has been proven acceptable if correct storage procedures are employed. Seals, both loose and installed in linear actuators, have been successfully tested for storage life in excess of eight years. Fluids, if free from contamination and additives that support agglomeration with time, should be considered storable for indefinite periods. Fluids of the 5606 type which incorporate a viscosity improvement additive, may be stored well in excess of five years if the amount of air, water, and particulate contamination are minimized prior to storage.

System exercise is a known contamination generator; therefore, serious thought should be given to the need for exercise before establishing a mandatory checkout procedure which includes periodic operation of the hydraulic system.

In summary, there is a substantial amount of storage test evidence that will support the conclusion that missile hydraulic systems may be inactively stored for more than five years without affecting subsequent system performance. This presumes that the system is adequately prepared for storage, and up-to-date design practices are followed. The only additional proof needed to finalize this conclusion is the five year storage test data of a representative hydraulic system from a current "operational missile."

6. REFERENCES

A substantial amount of the research performed in the field of long-term storage has been initiated through the Society of Automotive Engineers (SAE) A-6 Committee, Panel on Long-Term Storage. A number of the reports listed below are outputs of this research. An additional bibliography related to long-term storage is included for reference and information; however, because of time limitations this additional material was not used to prepare this report.

6.1 Reference Material (Included in report data)

1. "Long Term Storage of Hydraulic Systems in Second Generation Ballistic Missiles," SAE report by N. N. Fruktow and L. Purpura, September 1959.

2. "A Study of Long-Term Storage Effects on Missile Control Systems and Auxiliary Power Supply System Elements," Vickers, Inc., Aerospace Division, June 17, 1963.

3. "Engineering Evaluation Test Report, Part No. 2650173, Electrohydraulic Servoactuator System - Appendix I, All Weather Static Gas Leakage Tests, Hydraulic Accumulators," Parker Aircraft Co., Aerospace Components Division, December 1965.

4. "Storage of Aircraft Hydraulic Systems and Power Control Units at Davis-Monthan AFB," Space Technology Labs Interoffice Memo GM61-9732.4-66, signed by N. N. Fruktow, April 10, 1961.

5. "Methods of Preservation and Results of Long-Term Storage of Jet Aircraft Hydraulic Systems and Servovalves at U. S. Naval Air Facility, Litchfield Park, Arizona," Space Technology Labs Report 6120-0047-MU-000, November 1961.

6. "First Progress Report - Investigation of Hydraulic Equipment Removed from B-24 D 'Lady Be Good' Aircraft," Vickers Incorporated, July 7, 1960.

7. "Design of Missile Hydraulic Systems for Long-Term Storage," Convair Intra-Company Correspondence M246-670, signed by M. Voytish Jr., April 1, 1959.

8. "Report of the Subpanel on 2.5 to 5 Micron Procedure," SAE A-6D Contamination Control Panel - J. K. Van Loon, W. Kenyon, R. Connelly, W. Zittle, April 1962.

9. "Long-Term Storage Design Capability of Minuteman Power Elements," SAE A-6D report by C. J. Repert and R. M. Frazzini, October 16, 1962.