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Bench Scale Dynamic Evaluation Apparatus for Integral Fuel Tank Sealants

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The Air Force has a critical need for bench scale dynamic evaluation of integral fuel tank sealants under conditions closely simulating those encountered in actual aircraft integral fuel tanks. Both current state-of-the-art aircraft and anticipated future aircraft have integral fuel tank sealant requirements which demand materials that perform at or beyond the limits of available sealants. Dynamic testing which exposes the materials to conditions typical of those encountered in the aircraft during flight is essential to predict accurately the performance of the material in actual use. A unique bench scale dynamic test apparatus has been developed by Systems Research Laboratories, Inc., under an AFML contract, which can be programmed to simulate a great number of integral fuel tank environments. This device allows precise measurement and control of loads, temperatures, pressures, fuel exposure, and other parameters, yet is reliable and versatile. This capability for exposing sealant materials to typical loads during environmental testing allows accurate prediction of the performance of the material in actual use. This paper describes the dynamic test apparatus and its use to evaluate integral fuel tank sealants.

Introduction

OPTIMIZATION of modern aircraft has led to the widespread use of integral fuel tankage. This concept makes use of existing internal cavities in the wings and other parts of the aircraft for fuel storage by utilizing the aircraft structure as walls of the fuel tank. These cavities are rendered fuel tight by sealing potential leak paths such as seams, joints, and fasteners with elastomeric sealants. Different kinds of sealants such as fillet, faying surface, and channel (groove injection) have been developed for this purpose. Also, new sealant materials are continually being developed, both to solve problems on existing aircraft and to meet the requirements of new, high performance aircraft. These requirements include long life performance in the fuel tank environment at temperatures ranging from -65 to $+600°F$. Evaluation of sealant materials should include their exposure to the complex set of physical variables which occur in actual use, since failure can result from interactions and synergistic effects of the various physical properties (e.g., adhesion, strength, and elongation) and environmental parameters (e.g., temperature, pressure, and fuel). This is particularly important since sealant materials frequently operate near their physical limits.

Dynamic testing which exposes the sealant materials to mechanical loads typical of those encountered in the aircraft during the environmental exposure is essential to predict accurately the performance of the material in actual use. Whereas real time dynamic testing of full-scale test articles, including functional integral fuel tanks, is desirable, it is very expensive and is seldom accomplished. The evaluation of sealant materials in a bench scale dynamic apparatus would greatly reduce the cost and risks associated with full-scale durability tests and, therefore, make them more viable and less likely to be deleted from development programs. A number of dynamic deflection devices for testing sealant materials have been developed since the introduction of integral fuel tanks in the early 1940's. Most of these were relatively simple devices with limited mechanical load capabilities. Also, in most cases, the mechanical deflections were applied after static environmental exposures. In the early 1970's a dynamic sealant tester was developed by the Dow Corning Corp. under Air Force Materials Laboratory contracts which could be programmed to simulate actual flight environmental profiles while simultaneously subjecting the sealed joints to mechanical loads typical of those experienced in flight. It was also flexible enough to allow for a variety of sealed joint configurations and environmental conditions. That device proved that the dynamic testing concept was sound; however, it suffered from design and fabrication deficiencies. As a result, precise control and measurement of loads were not possible. Also, excessive downtime was required for maintenance and test setup. After a comprehensive re-evaluation, both Dow Corning and the AFML agreed that a second generation apparatus was required. Utilizing the technology developed in the Dow Corning program, Systems Research Laboratories, Inc. (SRL) designed and built an improved test apparatus under an AFML contract. This apparatus provides precise control and measurement of a wide range of mechanical loads and environmental conditions, thus allowing the evaluation of integral fuel tank sealants under laboratory conditions closely simulating actual aircraft integral fuel tanks during flight.

Dynamic Sealant Tester

Capabilities

Pressure

The test apparatus has two chambers which simulate the inside and outside of the fuel tank. The pressure in each

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chamber is independently controllable to allow simulation of a pressurized fuel tank and of reduced atmospheric pressure at high altitudes. Pressures can be varied over a range of 0-30 psia with a controlled differential between chambers.

Temperature

The temperature of the sealant being evaluated is controllable from −65 to +600°F, with either extreme being attainable within 5 min. Different temperatures can be generated at different times in the evaluation cycle to simulate an empty or a full fuel tank. (In the latter case, the fuel in an actual aircraft acts as a heat sink and attenuates temperature changes.) The sealant temperatures are recorded on a strip-chart recorder.

Mechanical Loading

Independent torsional (shearing) and joint-opening (stretching) strains can be applied to the seal. The rates can be independently varied from 0 to 20 Hz, with amplitude independently controlled from 0 to ±0.030 in. The sealant strains are measured by LVDT's, simultaneously displayed on digital meters and recorded on a strip-chart recorder.

Fuel Exposure

Fuel can be pumped into the chamber simulating the fuel tank at the appropriate time and, later, pumped out. The fuel is then discarded since it becomes contaminated and even degrades when high temperatures are used.

Automatic Operation

Conditions simulating those encountered by the sealed joint at various times during a typical flight can be programmed. These include fuel fill, mild heating in liquid fuel, fuel removal, high heating in fuel vapor, and cooling phases. The simulated flight cycle can be repeated automatically until sealant failure occurs. The evaluation is shut down automatically if fuel leakage through the seal is detected by a hydrocarbon detector. The detector sensitivity is adjustable to accommodate different leakage levels.

Construction of Testing Apparatus

Specimen Installation and Chamber

Figure 1 is a photograph of an assembled continuous fillet test specimen. A cup is attached to a disk by applying a fillet of the experimental sealant material around the perimeter of the cup. Figure 2 is a photograph of the system showing the evaluation chamber with associated equipment and the control console. Figure 3 shows the chamber and some of the other equipment in more detail and Fig. 4 is a schematic of the chamber showing internal details. The evaluation chamber is divided into an upper and lower section at the flanges just above the top of the legs. The test specimen is inserted in this junction with the disk horizontal and the cup above the disk. Thus, the disk forms the boundary between the upper chamber (which simulates the interior of the fuel tank) and the lower chamber (which simulates the outside atmosphere).

In the development of the apparatus, thermal distortion of the specimen disk proved to be very troublesome. Considerable effort was devoted to minimizing the effect of this distortion upon sealant evaluations. The specimen disk shown in Fig. 5 has been shown to apply minimal thermally induced strain to the elastomer, i.e., sealant. Its major feature is a slight depression in the central region. This depression, which ends approximately at the edge of the heater, allows the more strongly heated center portion to expand more uniformly with a resultant reduction in disk buckling.

The cup is gripped by an arbor which extends downward through the top of the upper chamber. The arbor grips the exterior of the cup. An expanding collett is located inside the cup to prevent loosening through fatigue and/or differential thermal expansion. The arbor has a double O-ring seal where it penetrates the top.

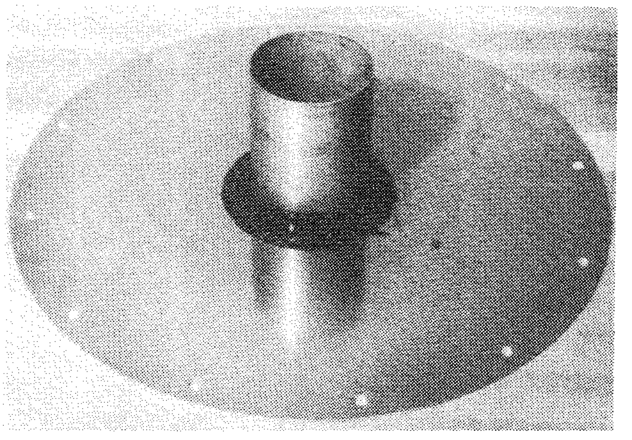

Fig. 1 Continuous-fillet test specimen.

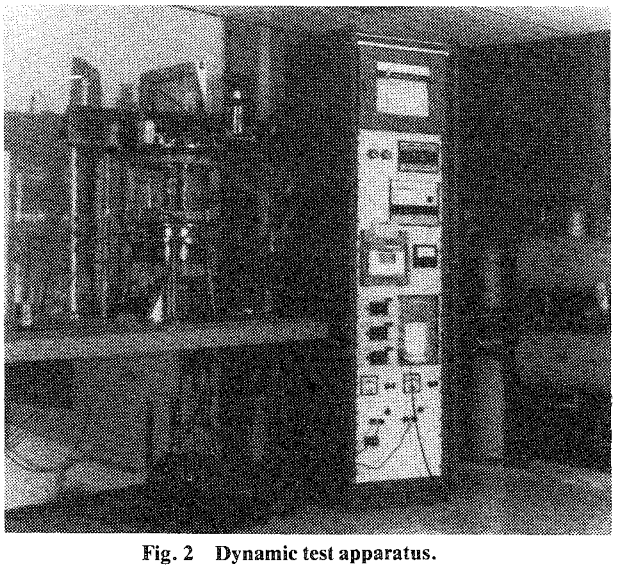

Fig. 2 Dynamic test apparatus.

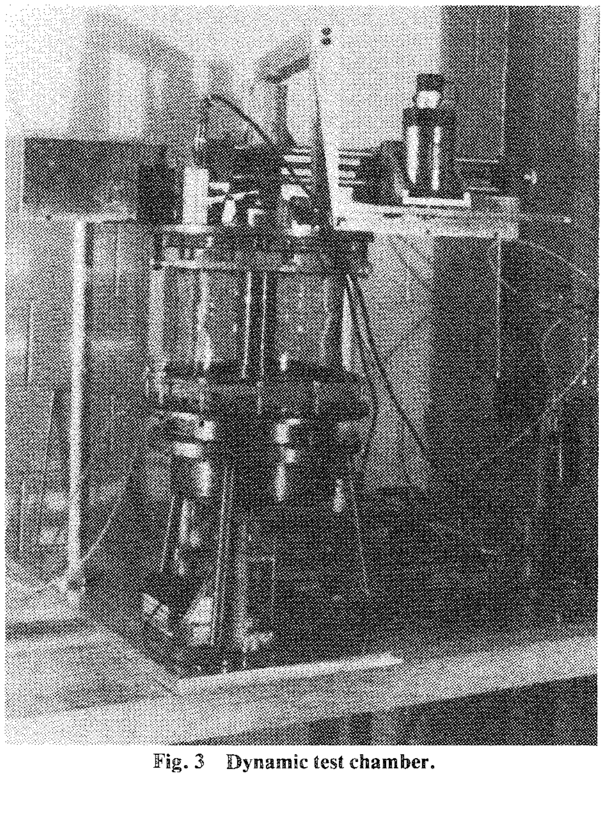

Fig. 3 Dynamic test chamber.

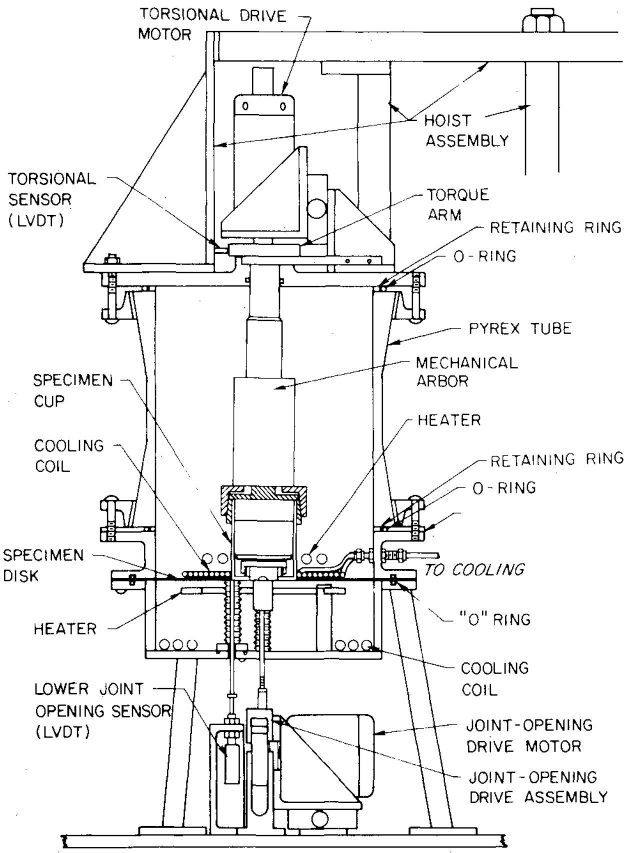

Fig. 4 Schematic of test chamber.

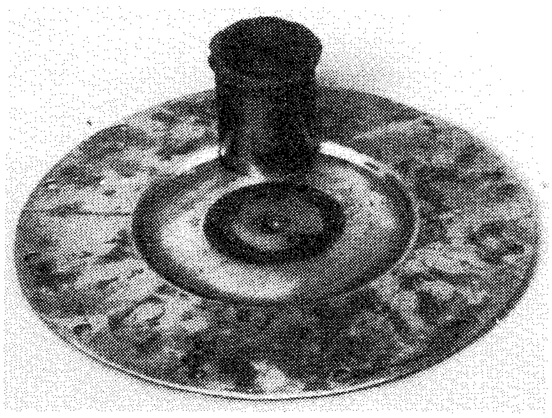

Fig. 5 Test specimen with recessed disk.

Applied Strains

Independent biaxial strains are applied to the sealant specimen by two variable-speed dc motors through cams and lever arms. Torsional strain is applied by twisting the arbor with a motor on top of the chamber. The amplitude adjustment is made by moving the motor so as to lengthen or shorten the lever arm. The torsion is thus applied to the cup with the disk fastened in place and, as a result, shear forces are applied to the sealant material. Tensile strains are applied by a drive attached to the disk through the chamber bottom. The disk center is pushed upward by the drive. The doming of the disk caused by this drive separates the perimeter of the rigid cup from the disk and thus opens the joint which stretches the sealant material. The motor for this drive is also attached through a cam and lever arm. The strain amplitude is adjusted, as in the case of the torsional strain, by moving the motor which changes the lever arm length.

The strains are measured by means of LVDT's, one for the torsional motion (measurement taken off the lever arm) and two for the joint-opening motion. Joint-opening measurements are made of the vertical motion of the disk under the edge of the cup and of the vertical motion of the arbor top which is also the vertical motion of the cup. The difference between these measurements yields the amount of joint opening. The strains are displayed instantaneously on digital meters and simultaneously recorded on a two-channel strip-chart recorder.

Pressure

Pressure in the two chambers is controlled by means of a quartz manometer controller (lower chamber to simulate atmospheric pressure at altitude) and a Wallace-Tiernan Manostat (upper chamber). The Manostat allows a preset difference between the upper and lower chamber, with the upper chamber being at the higher pressure to simulate a pressurized fuel tank. The pressure differential also serves to drive fuel through leaks in the seal which may develop. Vacuum pumps and prepurified tank nitrogen are connected to the controllers. A thermocouple gage controller monitors the pressure and terminates the evaluation if the pressure increases suddenly. This safety precaution guards against a leak which might allow oxygen into the system.

Temperature

Temperature is sensed by a thermocouple welded to the bottom of the disk directly under the seal. The temperatures are controlled by means of a thermal controller connected to electric heaters. Two potentiometers are employed to set the two different temperatures used to simulate the temperature of a full tank and of an empty tank. These two temperatures can be used at different times in the same evaluation cycle. The temperature is recorded continuously on a strip-chart recorder. Heating is accomplished by means of two heaters, one under the disk and the other above it. Cooling is accomplished by flowing a refrigerated fluid through a closely wound horizontal cooling coil just above the disk and water flowing through cooling coils inside the lower chamber and attached to the outside of the lower chamber.

Fuel and Leak Detection

Fuel is pumped into and out of the upper chamber by variable speed pumps. When the seal begins to leak, fuel appears in the lower chamber. The gases in this chamber are sampled continuously by a vacuum pump attached to a line through a throttle valve. A solid-state hydrocarbon detector optimized for jet fuel is located in a chamber in the line. The sensitivity of this detector is adjustable, and additional adjustment is obtained by using the throttle valve. Outputs can be taken from the detector electronics at a sensitive "warning" level and at a less sensitive "alarm" level. These levels are independently adjustable. The "alarm" signal is used to terminate the evaluation.

Automatic Operation

The proper sequencing of operations is maintained by a 24-channel program card controller which provides up to 24 h of automatic operation. By merely resetting the program card at the end of the cycle, continuous operation is possible until the hydrocarbon detector terminates the evaluation.

Evaluation Procedures

Evaluation begins with preparation of a test specimen (e.g., continuous fillet). First, the sealant to be evaluated is used to bond the disk to the cup. After curing the sealant, the specimen is installed in the tester. Before testing, the upper and lower chambers are purged by evacuating and then filling with nitrogen. The pressure controllers can be bypassed for this operation. For the duration of the evaluation, both chambers are filled with nitrogen. The pressure in the lower chamber, which simulates the region outside a fuel tank, is preset at a level (e.g., 1/3 atm) which simulates pressure at altitude. The upper chamber—which corresponds to the interior of the fuel tank—is maintained by the differential regulator at a pressure which is typically 3-5 psi above that in the lower chamber and thus simulates a pressurized fuel tank.

Initial tests have simulated flights of high performance aircraft. Some flight data on sealant failure are available for these conditions and, therefore, correlation of data from bench scale tests and actual flight data can be made. Also, since failure times for these conditions are much shorter, the testing apparatus and procedures could be checked out more quickly.

At the beginning of a typical high performance test cycle, fuel (e.g., JP-7) is pumped into the upper chamber. The test specimen is then heated to a temperature (e.g., 250°F) simulating that of a full tank. Independently programmed tensile and torsional deflections (e.g., 0.005 in. tension at 10 cycles/min and ±0.002 in. torsional at 2 cycles/min) are applied simultaneously to the specimen. This portion of the cycle is continued for a specified time (e.g., 30 min); then, the fuel is pumped out—except for a thin layer on the bottom of the upper chamber—and the temperature is elevated (e.g., to 550°F) to simulate flight with a nearly empty tank. The higher vapor temperature is held for another preset period (e.g., 90 min). The application of mechanical strains continues during this time. Afterward, the specimen is cooled by a cryogenically refrigerated fluid and water to simulate the cooling which occurs during subsonic flight and landing. Mechanical strains are also applied during the cooling cycle.

If the sealed joint has not failed, the cycle is then repeated automatically, beginning with the pumping in of new fuel, for a period of up to 24 h. If, after 24 h, the sample still has not failed, the program card is reset manually and the evaluation continues automatically. When the sealant fails, leakage of the fuel into the lower chamber is detected and, at the proper leakage level, the evaluation is terminated.

Typically, the results of interest will take the form of graphs of cycles to failure as a function of various parameters such as maximum temperature and strain amplitude. The proper conditions for use of a particular sealant material can thus be established under simulated flight conditions.

Sealant Evaluations

Using the above test apparatus, SRL has begun a program to evaluate candidate sealant materials and sealing concepts under dynamic conditions which simulate the environments encountered in actual aircraft integral fuel tanks during flight. This is accomplished by subjecting appropriate test specimens to a spectrum of variables carefully selected to simulate the desired end use conditions. In most cases data will consist of time to failure values for typical joint configurations subjected to cyclic exposures simulating flight profiles. Joint configurations include typical filleting, faying surface, and channel sealing techniques as well as multiple barrier systems incorporating two or more of these techniques. The evaluations are intended to be suitable for the screening of candidate materials for specific applications, determination of performance characteristics and limits of individual sealants and classes of sealants, and to provide guidance for the development of new sealant materials and sealing concepts.

These dynamic evaluations are based upon simulated flight profiles which include exposure to fuel and fuel vapor coupled with cyclic temperature and pressure conditions such as would be encountered in a typical aircraft mission, e.g., takeoff (ambient temperature and pressure), subsonic climb and/or loiter (low to moderate temperature, low pressure), supersonic cruise (high temperature, low pressure), and descent (moderate temperature and pressure). Evaluations conducted to date have been limited to high temperature filleting sealants using the continuous fillet test specimen. A channel sealant test specimen design is currently being finalized and evaluations of channel sealants are expected to begin by August 1979.

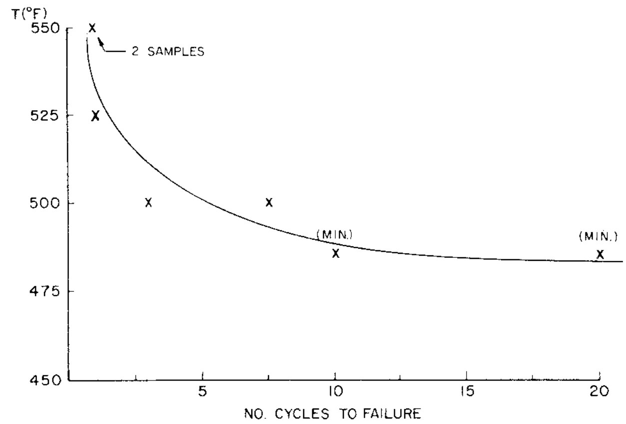

Fig. 6 Evaluation of polyester sealant using continuous-fillet specimen (fuel vapor temperature vs cycles to failure).

Specimens

The dynamic fuel tank sealant test apparatus has the flexibility to accommodate a variety of test specimens for the evaluation of various types of sealed joints. The test specimens are designed to simulate typical joint configurations found in aircraft integral fuel tanks. Appropriate aluminum and/or titanium alloys, surface finishes, corrosion coatings, etc., are used for each joint configuration. In addition to the continuous fillet specimen shown in Fig. 1, preliminary designs have been completed for a fillet corner configuration specimen and a channel sealant specimen.

Results

Figure 6 gives results to date on evaluations of continuous fillet specimens of 3M Co. Polyester EC 2288. Specimens have been tested at vapor temperatures of 485 to 550°F. The liquid temperature was held constant at 250°F, and strain amplitudes were held constant at ±5 mils for the torsional and 5 mils for the joint-opening strains. The liquid temperature phase was 30 min and the vapor phase 90 min. The cycles given in the graph are the ones in which the failures occurred. These data correlate directly to flight test data from the aircraft for which the flight cycle was selected.

Summary and Conclusions

Elastomeric materials used in sealing integral fuel tanks in today's high performance aircraft are exposed to complex environmental conditions such as mechanical loading in the presence of fuel and high temperatures. The Air Force has a critical need for rapid, economical, and realistic evaluation of these sealant materials. To provide an economical facility for dynamically evaluating these sealants, a unique system has been developed which subjects the sealant material in the laboratory to mechanical forces, pressures, temperatures, and fuel exposure conditions closely simulating those experienced in aircraft integral fuel tanks during flight. The system can simulate a complete flight profile including fuel loading, takeoff, cruise and high speed flight, landing, and shutdown. The system is capable of repeating these simulated flight conditions with a high degree of accuracy. The equipment allows automatic evaluation of elastomeric sealants using a variety of joint configurations.

This bench scale dynamic evaluation capability allows accurate prediction of the performance of sealant materials in use. Preliminary screening of sealant materials for new aircraft can be accomplished in this apparatus and, therefore, the apparatus permits a reliable selection of the optimum sealant and/or sealing system for the aircraft. The capability provided by this apparatus also can contribute directly to operation and maintenance cost reductions since field use conditions can be simulated when solving sealant problems on operational aircraft. Therefore, the need for costly and time-consuming flight tests is eliminated or reduced. Another, and perhaps the most important, feature of this dynamic evaluation apparatus is that it can serve as a research tool for studying sealant materials and their performance characteristics. For example, it can be used to establish the critical parameters for long service life for each important class of sealant materials (e.g., temperature range, adhesion, elongation, and tear resistance). It is also useful for the evaluation and comparison of new experimental sealant materials and for providing data to be used in life prediction techniques based upon accelerated testing.

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