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Advanced Duct Sealant Testing

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**Environmental Energy
Technologies Division**

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER program, managed by the California Energy Commission (Commission) , annually awards up to $62 Million to conduct the most promising public interest energy research by partnering with Research, Development and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy Related Environmental Research
- Strategic Energy Research

What follows is the final report for the Advanced Duct Sealant Testing, 500-010-002, conducted by the Lawrence Berkeley National Laboratory. This report is entitled Advanced Duct Sealing. This project contributes to the Buildings End-Use Energy Efficiency program.

Executive Summary

Duct leakage has been identified as a major source of energy loss in residential buildings. Most duct leakage occurs at the connections to registers, plenums or branches in the duct system. At each of these connections a method of sealing the duct system is required. Typical sealing methods include tapes or mastics applied around the joints in the system. Field examinations of duct systems have typically shown that these seals tend to fail over extended periods of time. The Lawrence Berkeley National Laboratory has been testing sealant durability for several years. Typical duct tape (i.e. fabric backed tapes with natural rubber adhesives) was found to fail more rapidly than all other duct sealants.

This report summarizes the results of duct sealant durability testing of five UL 181B-FX listed duct tapes (three cloth tapes, a foil tape and an Oriented Polypropylene (OPP) tape). One of the cloth tapes was specifically developed in collaboration with a tape manufacturer to perform better in our durability testing. The first test involved the aging of common "core-to-collar joints" of flexible duct to sheet metal collars, and sheet metal "collar-to-plenum joints" pressurized with 200°F (93°C) air. The second test consisted of baking duct tape specimens in a constant 212°F (100°C) oven following the UL 181B-FX "Temperature Test" requirements. Additional tests were also performed on only two tapes using sheet metal collar-to-plenum joints. Since an unsealed flexible duct joint can have a variable leakage depending on the positioning of the flexible duct core, the durability of the flexible duct joints could not be based on the 10% of unsealed leakage criteria. Nevertheless, the leakage of the sealed specimens prior to testing could be considered as a basis for a failure criteria. Visual inspection was also documented throughout the tests. The flexible duct core-to-collar joints were inspected monthly, while the sheet metal collar-to-plenum joints were inspected weekly. The baking test specimens were visually inspected weekly, and the durability was judged by the observed deterioration in terms of brittleness, cracking, flaking and blistering (the terminology used in the UL 181B-FX test procedure).

The current study is a continuation of ongoing research at Lawrence Berkeley National Laboratory that has the following objectives and outcomes:

Objectives	Outcomes
Evaluate existing UL 181B-FX rated tape products using a revised test method.	The core-to-collar tests are not complete and firm conclusions cannot be drawn until the aging tests have been finalized in the next phase of testing. Although the core-to-collar connections had no significant failures in terms of leakage some samples showed significant visual degradation.
Evaluate the UL 181B-FX high temperature test.	All the UL 181B-FX rated tapes except the foil tape showed significant visual degradation. This indicates that the interpretive nature of UL 181 B-FX high temperature test makes UL 181 B-FX an unreliable indicator of sealant performance.
Evaluate new duct sealant products.	The new duct sealant tape showed improved performance on collar-to-plenum joints, but still failed after 60 days of testing.
Develop a standardized test method for evaluating duct sealant durability (under the auspices of the American Society for Testing and Materials (ASTM)).	An ASTM draft standard has been developed that will standardize test procedures and increase reliability of testing. This standard should be completed by January 2004.

Key project conclusions:

- None of the tested tapes are acceptable for collar-to-plenum connections and the Energy Commission's Title 24 Standards should not allow this application.
- The standard (non-metallic) core-to-collar clamps have poor high temperature performance and almost all the clamps failed in our testing.
- UL 181 B-FX cannot be used as an indicator of acceptable durability until the following issues are resolved: 1) Products listed as Passing UL 181B-FX testing clearly fail the high temperature test that is part of the UL 181 B-FX testing, and 2) UL 181 B-FX must include testing of clamps (that are a required part of the UL 181 B-FX closure system).

Recommendations:

- Existing code language restricting the use of duct tapes should be retained.
- Only metal clamps should be allowed on core-to-collar connections until new requirements for non-metallic clamps are evaluated.

- The testing of samples should be continued until the full two years of testing are complete.
- Further inquiry is needed to determine how some of the tested sealants were able to obtain the UL 181 B-FX listing with such obvious failures during the high temperature testing.

The benefits to California from the work in this study are:

- We contributed to the retaining of existing code language restricting the use of duct tapes. This helps to ensure that new duct systems will not have substantial increases in leakage as they age, thus reducing the future energy use and peak power liabilities for the state, as well as ensuring continued energy cost savings for consumers.
- When the ASTM standard is completed the California Energy Commission (and other building code authorities) will have a standard that they can refer to directly to ensure the durability of duct sealants in California buildings.
- Improved duct sealants that can be used in California buildings have been developed as a result of this research.
- Knowledge of this work in the building industry is raising awareness of duct sealing issues and is leading to tighter duct systems being installed in California buildings, as well as ensuring that these systems remain tight in the future.

Abstract

Duct leakage is a major source of energy loss in residential buildings. Most duct leakage occurs at the connections to registers, plenums, or branches in the duct system. At each of these connections, a method of sealing the duct system is required. Typical sealing methods include tapes or mastics applied around the joints in the system. Field examinations of duct systems have shown that taped seals tend to fail over extended periods of time. The Lawrence Berkeley National Laboratory (LBNL) has been testing sealant durability for several years. Accelerated test methods were used that continuously expose duct sealants to elevated temperatures (200 to 212°F (93 to 100°C)). We found that typical duct tape (i.e., fabric backed tapes with natural rubber adhesives) fails more rapidly than all other duct sealants. We also tested advanced tape products being developed by major manufacturers. The results of these tests showed that the major weaknesses of the tapes that fail are the use of natural rubber adhesives and the mechanical properties of the backing. The test results also showed that the current UL listings are inadequate for indicating durability and many tapes showed significant failure when testing using UL 181 B-FX procedures. In addition, the clamps required (but not evaluated) by UL-181B-FX had many failures and their durability also required evaluation. An accelerated test method developed by LBNL is being used as a basis for an ASTM standard under sub-committee E6.41.

Keywords: ducts, air leakage, duct tape, durability, longevity, UL 181 B-FX

Introduction

Background

Air leakage in ducts has been identified as a major source of energy loss in residential buildings. Thirty to forty percent of air flow leaks in and out of ducting systems in residential buildings, and most of the duct leakage occurs at the connections to registers, plenums or branches in the air distribution system (Walker and Sherman 2000). This study is a continuation of previous studies conducted at LBNL (Walker et al. 1998a and 1998b, Walker and Sherman 2000, and Sherman et al. 2000), whose objectives are to develop new test methods for duct sealant durability, evaluate different sealant types (e.g., tape, mastic, aerosol), facilitate the development of consensus standards (e.g., ASTM), and technology transfer.

Underwriters Laboratory (UL) have developed safety standards for closure systems for use with rigid air ducts and air connectors, and flexible air duct and air connectors; UL 181A and UL 181B, respectively (UL 1993 and 1995). The current UL 181B-FX standard deals with field assembled flexible duct systems. UL 181B-FX is of a special importance to residential buildings since residential duct systems in the U.S. are normally field assembled. The standard covers pressure sensitive tape and mastic. Note that the UL 181B-FX standard only applies to tapes that have a mechanical clamp at the inner core of flexible duct to collar connection (but no clamp is required for the outer moisture barrier). However, none of the UL tests require the clamp to be in place, nor are the clamps tested. Six tests are prescribed for pressure sensitive tape: tensile strength, peel adhesion at 180° angle, shear adhesion, surface burning, mold growth and humidity, and temperature tests. However, the standard has very limited tests of the durability of duct sealants. For example, the “shear adhesion test” requires duct tape to sustain specified load without evidence of separation or slippage in excess of 1/8 in (3.2 mm) for 24 hours only. While the UL tests address some important aspects of sealant performance, they do not adequately address durability issues.

The Air Diffusion Council (ADC 1996) has standards providing recommendations for the installation of ducting systems, and requires the use of two wraps of duct tape over flexible duct core-to-collar joints. ADC does not provide recommendations for the collar-to-plenum joints.

Prior Work

Previous duct sealing tests conducted at LBNL covered two types of joints, core-to-collar, and collar-to-plenum, using sheet metal ducts and fittings. For the core-to-collar joints, the tape joined two concentric materials, thus exhibiting a 2-dimensional joint. However, the collar-to-plenum joints are typical when a metal collar attaches to a duct branch, splitter box, or a supply or return plenum. The collar-to-plenum joint was the most difficult to seal with duct tape because the leaks to be covered are not in a flat plane and the tape must be folded in order to conform to the joint. The round collar is mated through a circular hole to a flat piece of metal, with a set of flexible tabs that mechanically hold the collar in place with the use of sheet metal screws. The gaps between the tabs leave gaps of 1/8” to 1/4” (3 to 6 mm).

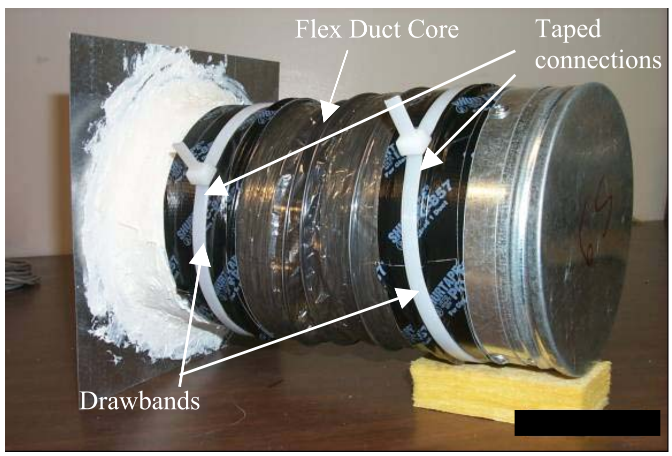

Figure 1 - Example of a core-to-collar test sample showing the two taped connections and the mechanical clamps.

Figure 2 - Example of collar-to-plenum connections on a system where the tape sealant has fallen off, and a collection of collar-to-plenum test samples from LBNL.

Previous work at LBNL has progressed in several phases, with the exact experimental details changing as the test procedures were refined:

The first durability testing (in 1996) was for evaluating the aerosol sealant technique developed at LBNL. This test alternately blew hot or room temperature air through sample joints with a 20 minute cycle time.

The second phase of testing (1997-1998) was initiated to examine a wide range of sealants and to make the testing more thorough by alternately blowing hot (140°F (60°C)) or cold (32°F (0°C)) air through test sections, with pressures across the sealed leaks of about 0.8 inches of water (200 Pa). The addition of cooling allowed the tests to examine the effects of condensation and frost formation on durability. The new apparatus used for the second phase of testing allowed simultaneous testing of eight samples. The second phase also included some simple baking tests where sample duct connections (the same as used in the cyclic temperature apparatus) were exposed to continuous high temperatures (between 140 and 176°F (60 and 80°C)) in an oven, with no temperature cycling and no pressure difference across the sealed leaks.

The third phase of testing (1998–2001) was based on a new apparatus that could simultaneously have samples either continually cooled (32°F to 41°F (0°C to 5°C)), continually heated (150°F to 180°F (66°C to 82°C), or cycled between the two extremes. The pressures across the sealed leaks varied over the range 0.4 to 0.8 inches of water (100 to 200 Pa) depending on the testing mode. This larger apparatus could accommodate up to 30 samples in total and over 50 samples were tested. The testing during this phase confirmed previous results

– the only sealants to fail are cloth backed natural rubber adhesive tapes, and heating only produces the most rapid failure.

Current Work

The current study uses the same apparatus as the third phase – but has heating only and no cooling. Eighteen samples are simultaneously heated and pressurized, and the high temperature is set to 200°F (93°C). This was done to more closely match that used in the UL 181B-FX temperature tests (212°F (100°C)) and in response to comments received on drafts of the ASTM standard prepared in parallel with these laboratory tests. The average pressure difference the specimens are exposed to in the apparatus is 0.34 inch water (84 Pa). In addition, we are replicating the UL 181B-FX temperature test by baking tape samples on substrates, i.e. not placed on duct connections.

The previous LBNL tests of duct tape durability evaluated six types of sealants: (1) tape with vinyl or polyethylene backing with fiber reinforcement and rubber-based adhesive, (2) oriented polypropylene (OPP) tape with acrylic adhesive, (3) foil tape with acrylic adhesive, (4) butyl tape with foil backing and thick butyl adhesive, (5) mastic, an adhesive that dries to a semi-rigid solid, and (6) aerosol sealant, a sticky vinyl polymer blown inside the duct system. Some of these products carried UL 181B-FX or UL 181B-M approval.

In the current study only UL 181B-FX products were evaluated because many building codes now require that duct sealants be UL 181B-FX listed. Five different UL-listed duct tape products were used in the aging of flexible duct joints and the baking tests, generically called in this report as Tape 1, Tape 2, Tape 3, and Tape 4. For the aging of the sheet metal collar-to-plenum joints, two tapes were used; Tape 1, and an additional duct tape, Tape 5. Tapes 1 and 2 are conventional duct tapes. Tape 3 is an OPP, acrylic adhesive tape. Tape 4 is a foil-backed, butyl adhesive tape. Tape 5 is a prototype cloth-backed, butyl adhesive tape developed by a duct tape manufacturer specifically to meet the requirements of the current study.

For collar-to-plenum connections, the failure criterion was based on measuring leakage at a fixed reference pressure of 25 Pa (0.1 In. water). This air leakage was measured before any sealant was applied (Q_{pre}) and after initial sealing (Q_{post}). The difference between these two measurements (Q_{sealed}) is the leakage air flow sealed by the sealant. Failure was said to occur when the measured leakage of a sample is greater than the sum of Q_{post} plus 10% of Q_{sealed}. The inclusion of Q_{post} in the failure criterion calculation corrected for other small leaks in the sample as well as any remaining leakage past the duct sealant after it was applied). The visual features of the specimen failure were also documented; drying and hardening of the adhesive, shrinking of the tape baking, delamination of the tape layers (backing/fiber/adhesive), and peeling of the tape off the medium it is applied to.

Project objectives were to:

- Evaluate existing UL 181 rated products using a revised test method .
- Investigate the effect of cleanliness of the substrates prior to sealant application. This objective was removed during this project in order to perform additional durability tests.
- Evaluate new duct sealant products.
- Develop a standardized test method for evaluating duct sealant durability
- Evaluate the UL 181B-FX high temperature test.

Project Approach

Durability Test

Figure 3 shows samples mounted on the aging test apparatus. Heated air is continuously circulated through the test apparatus to both heat and pressurize the leakage sites. The apparatus is divided into an upper and lower chamber that each contains nine samples. The inside of the test samples are exposed to high pressure heated air and the outside (shown in Figure 3) is in an insulated chamber that also becomes heated during the experiments by conduction through the test samples. This means that there is little temperature gradient across the samples. The hot air temperature is controlled using electric resistance heaters mounted directly in the air stream. The surface temperatures of each sample, the air temperature and the pressure across the leaks are continuously monitored using a computer based data acquisition system. The actual leakage measurements are conducted periodically (typically on a monthly or weekly basis) by removing the samples from the test machine. They are then allowed to cool to room temperature before being placed in a separate testing device that pressurizes the samples to 0.1 in. water (25 Pa) and measures the air flow rate required to maintain this 0.1 in. water (25 Pa) pressure difference (Figure 4). Small deviations leakage flow due to the actual pressure obtained during the test not being exactly 0.1 in. water (25 Pa) are corrected to the 0.1 in. water (25 Pa) reference. This 0.1 in. water (25 Pa) air flow is the leakage of the sample that is then recorded and compared to initial 0.1 in. water (25 Pa) air flow measurements of the connections before and after initial sealing.

Figure 3. One chamber of the high temperature aging test apparatus.

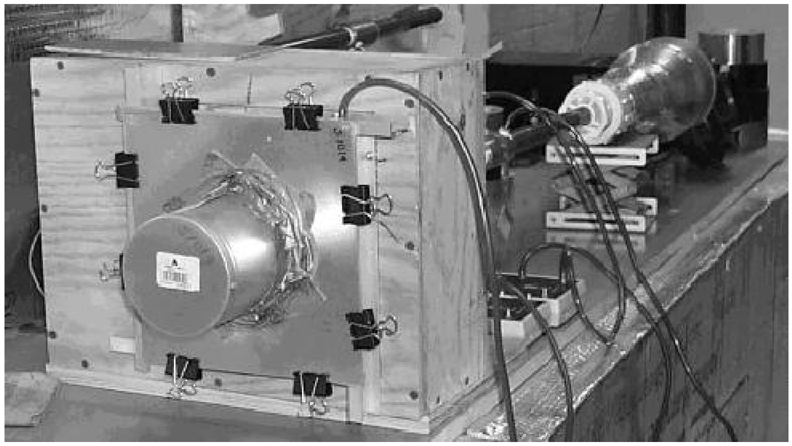

Figure 4 - Leakage test device for pressurizing test samples. (Test sample is a collar-to-plenum joint.)

Figure 5 shows a schematic of the hot air circulation path in the aging test apparatus. The upper and lower test chambers are connected by insulated ducting so that the same air flows through both chambers and only one heater is required. In the previous phase of testing, the lower chamber had cold air circulating through it.

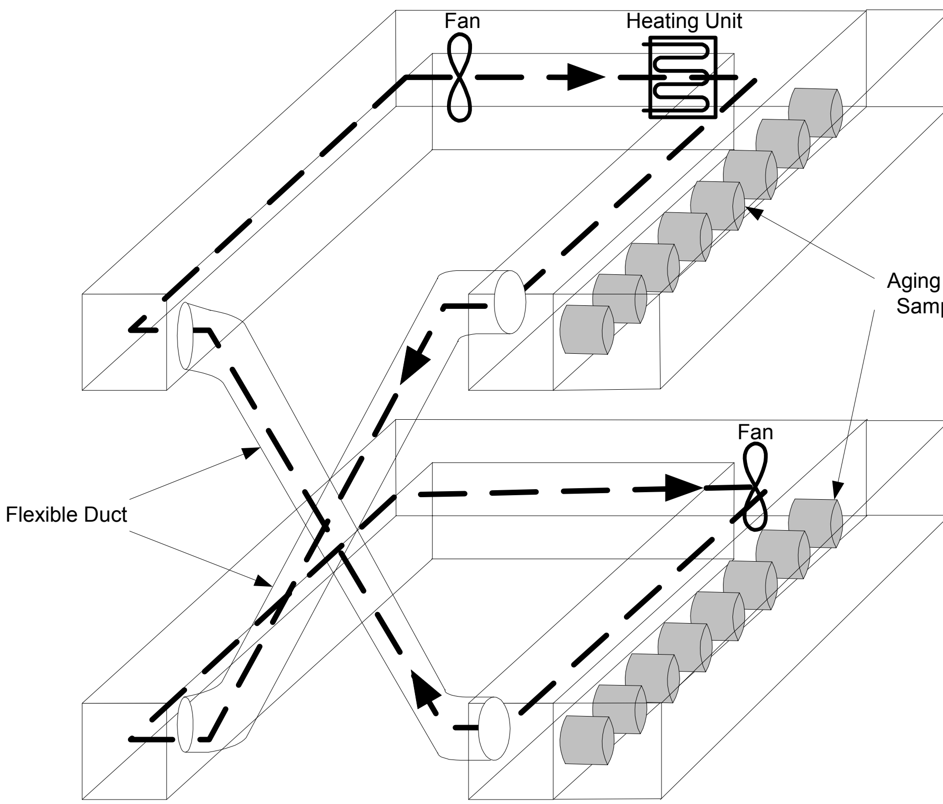

Figure 5. The hot air circulation in the modified aging test apparatus.

Figure 6 shows the baking test oven that provides constant circulating air temperature of 212°F (100°C) for the baking specimens following the UL 181B-FX "temperature test" protocol. All walls of the oven are made with 4" (100 mm) thick foil-faced foam sheathing. The bottom of the oven, sitting on the floor, is made thicker (6" (150 mm)) for added insulation. The oven is

44” (112 cm) high, 72” (183 cm) wide, and 10” (25 cm) deep. It contains four racks made of two strips of aluminum that hold the testing specimens. Six temperature sensors equidistantly placed on both sides of the oven provide readings of the temperature profile inside the oven. Measured results show that the temperatures do not vary by more than 5°F (2.5°C) from the average temperature of 212°F (100°C). The oven has an electric heating unit controlled by a relay box to turn off at 214°F (101°C) and on at 210°F (99°C), and also protected by a safety snap thermostat rated at 250°F (121°C). The temperature values are recorded at a one-minute interval.

Figure 6. The high temperature baking apparatus.

The air leakage measurements were conducted periodically (typically on a monthly or weekly basis) by removing the samples from the test apparatus. They were then placed in a separate leakage testing device (Figure 4) that pressurized the samples to 0.1 in. water (25 Pa) and measured the airflow rate required to maintain the 0.1 in. water (25 Pa) pressure difference. 0.1 in. water (25 Pa) was chosen because this pressure difference is used as a reference pressure in field testing of duct system leakage (Test Methods for Determining External Air Leakage of Air Distribution Systems by Fan Pressurization (ASTM E1554), Method of Test for Determining Design and Seasonal Efficiencies for Residential Thermal Distribution Systems (Proposed ASHRAE Standard 152P) [8, 9]) and it is typical of average pressures across residential duct leaks.

This 0.1 in. water (25 Pa) airflow rate was also measured before any sealant was applied and after initial sealing. The air leakage after initial sealing was usually very small (about 0.5% of the unsealed air leakage) and accounted for the remaining leakage in the leakage test device and test sample. The difference between the air leakage before and after sealing is therefore the amount of sample leakage that has been sealed by application of the sealant. We set a failure criterion for air leakage at 10% of this difference based on what we considered to be a realistic level of leakage for an individual joint in a real system, and as a leakage level after which samples tended to fail rapidly in our testing.

Temperature Effect on Leakage Measurements

Because the aging test involves heating the specimens continuously at 200°F (93°C), it takes some time for the specimens to return to room temperature. Therefore the elapsed time between removal from the test chamber and measurement of leakage could have an effect on the results. To examine this effect, a specimen was tested six times at 15-minute intervals, with the first measurement taken at its highest temperature (200°F (93°C)). The experiment took place in the laboratory where room temperature is 77°F (25°C). Figure 7 shows the decay in the leakage flow as a function of cool-off time. The leakage flow at the highest temperature is 16% higher than the last value taken 1 hour and 15 minutes later. The difference in leakage is attributed to the "re-sealing" of the joint as it shrinks and hardens at lower temperatures. For consistent results the samples need to cool to room temperature before being leakage tested. Because this effect was not discovered until several months of tested had elapsed, some of these results have additional uncertainty in measured sample leakage.

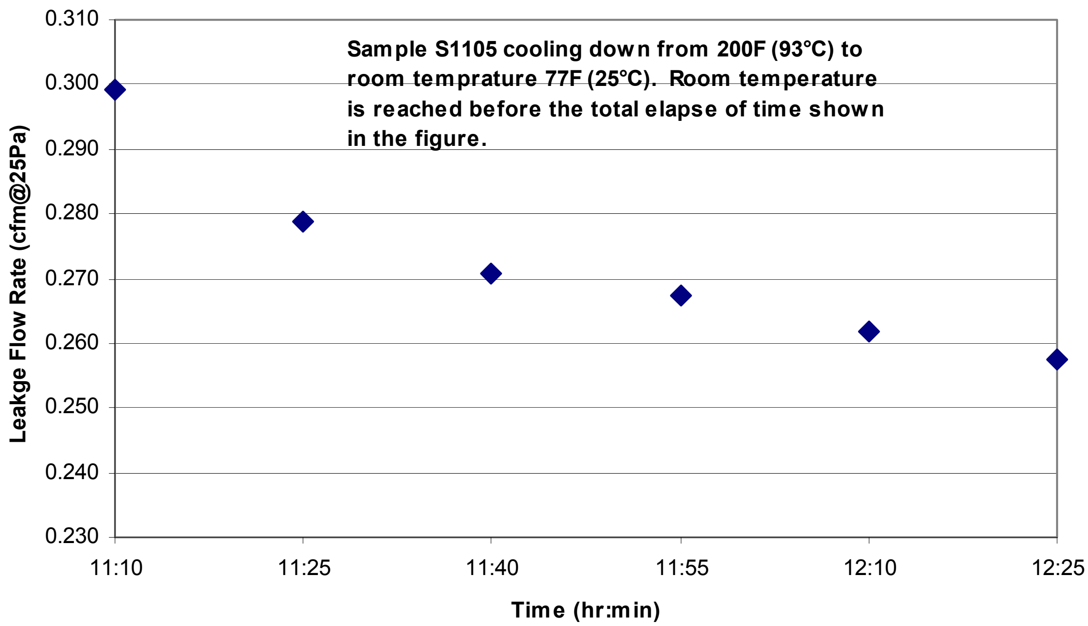

Figure 7. Decay in the measured leakage as the specimen cools down from 200F (93°C) to room temperature.

Aging Test Experimental Conditions

The difference between the tests conducted in this study and previous tests, is in the type and construction of the specimens and the temperature of the tests. Previously, in Walker et al. (1998a and 1998b), Walker and Sherman (2000), and Sherman et al. (2000), the aging tests concentrated on a 4" (100 mm) collar-to-plenum joint. Because UL 181B-FX products are the focus of this study, the test joint was changed to the flex duct to collar connection that the UL testing concentrates on. Specifically, a 6" (150 mm) diameter flexible duct core to sheet metal collar joint is used.

Flexible ducts consist of three layers: inner membrane called "core", a layer of insulation and an outer layer acting as a moisture barrier called a "jacket". The test samples were sealed with two layers (one continuous piece) of duct tape applied to the core of the duct with the insulation and outer moisture barrier removed. The taped joint is reinforced with a mechanical plastic clamp installed over the tape as required for UL 181 B-FX installations. Figure 1 shows a laboratory construction of the 6” (150 mm) flexible core-to-collar joint aging test specimens, which contains two core-to-collar joints (the joint being tested) and one collar-to-plenum joint (not tested and sealed with mastic). The white irregular ring of material at the back (left) is mastic that has been applied over the collar-to-plenum joint. The end of the duct is capped with a metal cap that is sealed before testing. Figure 8 shows a schematic of the flexible duct core-to-collar joint as it is fits on the aging test apparatus. Figure 8 shows how the whole specimen is enclosed in insulation that forms a test chamber.

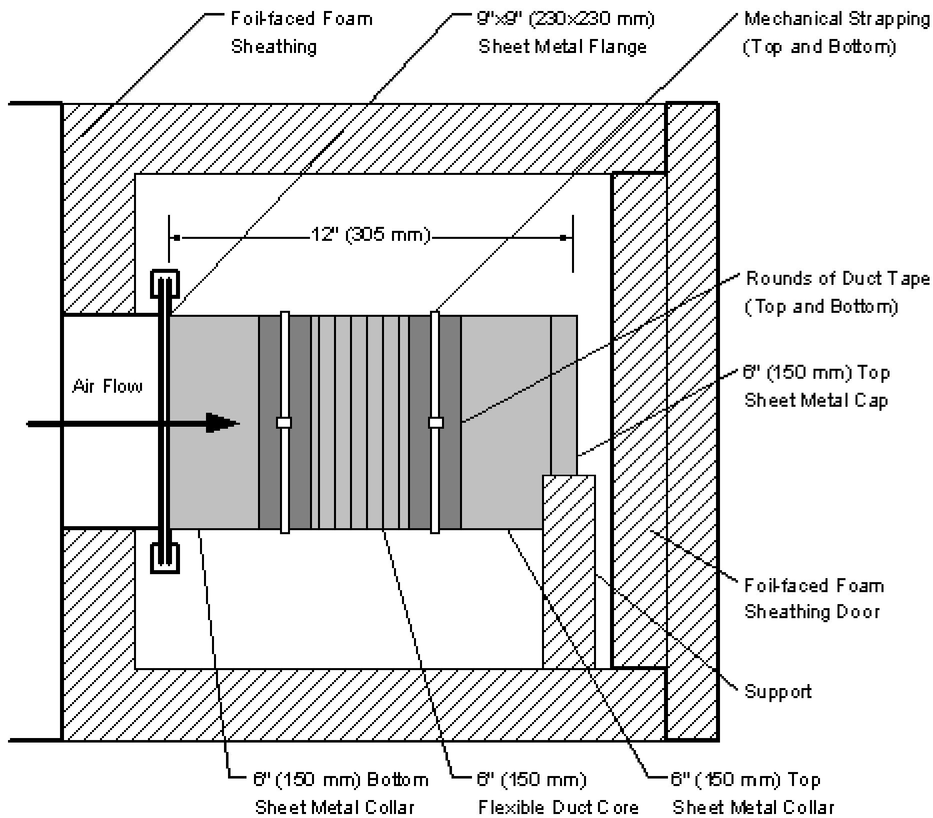

Figure 8. A side-view schematic of a flexible duct core to sheet metal collar joint specimen positioned on the aging test apparatus.

We also tested samples without mechanical clamping because this configuration is commonly found in field installations. Also, clamps are only required on the inner core and not on the outer moisture barrier by UL 181 B-FX. The taping technique was changed for some samples to include discontinuous wrapping and only a single layer of tape instead of two. Table 1 shows the 18 combinations tested in this study.

In addition to the aging tests of the flexible duct core-to-collar joints we also repeated the collar-to-plenum 4” (100 mm) joints aging tests that were conducted in previous studies, in order to test a new duct tape product that can sustain 200°F (93°C) temperature (Tape 5).

Table 1. Aging Test: Summary of core-to-collar combinations					
Tape #	Type	Specimen #	Clamping	# of Tape Wraps	Continuous Wrapping
Tape 1	Duct Tape	S7001	√	2	√
		S7002	√	2	
		S7003	√	1	√
		S7004	√	1	
		S7005		2	√
		S7006		2	
		S7007		1	√
		S7008		1	
Tape 2	Duct Tape	S7009	√	2	√
		S7010	√	2	
		S7011		2	√
		S7012		1	
Tape 3	OPP Tape	S7013	√	2	√
		S7014	√	1	√
		S7015		2	
Tape 4	Foil-Butyl Tape	S7016	√	2	√
		S7017	√	1	
		S7018		1	√

Baking Test

For each duct tape (Tape 1, Tape 2, Tape 3, and Tape 4), twelve specimens were made by applying a strip of tape to three 4 by 4 inch (100 by 100 mm) samples of each of the following materials: aluminum foil, polyethylene, polyethylene terephthalate (PET), and sheet metal (galvanized steel). Another 4 by 4 inch (100 by 100 mm) control sample of each of the substrate materials is also tested without applying the tape to it. The control sample serves as a means to quantify the deterioration attributed to the substrate in isolation from the duct tape. A specimen set in the baking test, therefore consists of three similar samples and one control sample, all carried by a sheet metal tray in the oven (Figure 9). Since the substrates used in this test are very thin and light weight, they are attached from two sides to the sheet metal tray so that the fan can not blow them away from their locations.

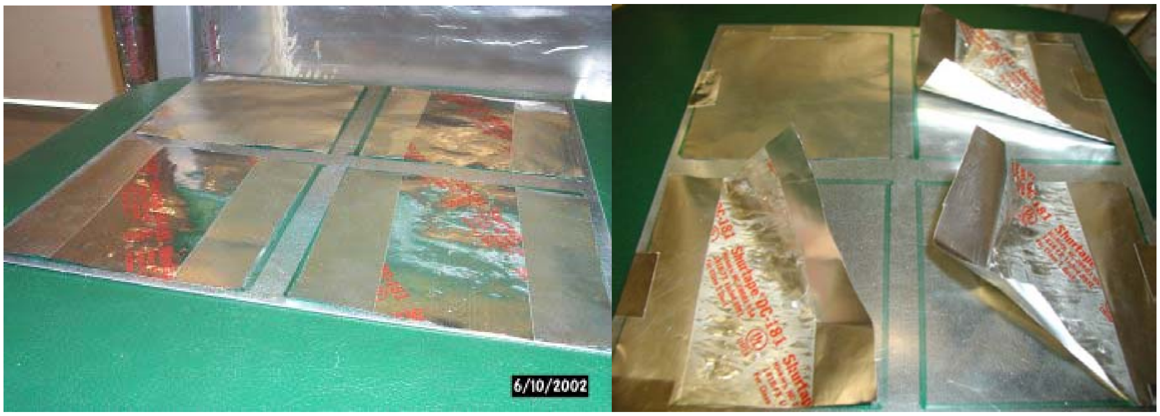

Figure 9. A baking specimen following the UL 181B temperature test protocol consisting of three samples of tape (Tape 3) and one control sample of the substrate (Aluminum Foil) before testing (left) and after four weeks of testing (right).

In addition to the specimens following the UL 181B temperature test protocol, we included “hanging specimens” (Figure 10) of all four tapes in the oven to examine their deterioration in isolation from the substrate they are applied to.

Figure 10. Hanging specimens of Tapes 1 to 4 in the high temperature baking apparatus before testing (left) and after three weeks of testing (right).

In this type of test, visual inspection is an indicator of the tape failure. The baking test specimens are visually inspected weekly, and the durability is judged by the observed deterioration in terms of hardening, brittleness, peeling, shrinkage, wrinkling, delamination, flaking, cracking, bubbling, oozing and discoloration.

Support activities for the Commission

- In March 2002 we provided written and oral (at a CEC hearing)) testimony for the CEC In The Matter Of: “REVIEW OF CONCERNS RAISED BY TYCO ADHESIVES ON BUILDING ENERGY EFFICIENCY STANDARDS REQUIREMENTS FOR CLOTH BACK RUBBER ADHESIVE DUCT TAPE”. In April 2002 we also provided a written reply to TYCO’s response to the CEC workshop.

- We developed and maintained a project-use website to provide instant access to test results for CEC staff.
- We provided Summaries of previous testing of UL rated tapes from 1997 and 2000 to CEC staff.
- We collaborated with the CEC and the industry on developing a test procedure for tapes.
- We tested a new tape developed directly because of this research project.
- We prepared a Technical Report after 6 months of testing, LBNL Report 51099
- We provided CEC staff with ASTM Review drafts of sealant durability (and duct leakage) test methods.
- We presented a technical paper at an ASTM Sealant Symposium on durability of building sealants in Orlando, FL: Walker, I.S. and Sherman, M.H., (2003), Sealant Longevity for Residential Ducts, Durability of Building and Construction Sealants and Adhesives, ASTM STP 1453, A. Wolf Ed., American Society for Testing and Materials, West Conshohocken, Pa. LBNL 50189.

Project Outcomes

Evaluation of existing UL 181 rated products using a revised test method

Measuring the leakage in a flexible duct core-to-collar specimen prior to applying the duct tape (sealing), cannot be taken as a baseline leakage in the analysis. The reason is that the flexible duct does not fit firmly on the sheet metal fitting and thus the unsealed joint is relatively much leakier than one made with two sheet metal sections. In addition, being flexible, the way the core is placed around the sheet metal collar can make a considerable difference in the amount of leakage. An unsealed specimen was tested and the leakage changed by up to 30% when the test was repeated by only changing the positioning of the flexible core around the sheet metal collar, and up to 40% among different flexible duct configurations (stretched, bent, compressed). Therefore we considered the base case to be the initial sealing prior to testing; the failure criteria could then be characterized by the changes in the leakage, as well as visual inspection. Table 2 shows the detailed repeatability and variability results of the unsealed leakage of a flexible duct core-to-sheet metal collar specimen.

Table 2. Aging Test: Leakage Variation of an Unsealed Flexible Duct core-to-sheet metal collar samples		
Core Position	**Compressibility and Bending of Flexible Duct**	**Leakage Flow (cfm@25Pa (0.1 in water))**
1	Straight – Fully Stretched	2.6
	Bent 45°	1.5
	Maximum Compression	2.3
	Average Compression	2.9
2	Straight – Fully Stretched	2.0
	Bent 45°	1.7
	Maximum Compression	1.9
	Average Compression	2.0

In order to systematically record the visual deterioration of the samples, monthly pictures of all 18 specimens were taken. Typical minor deteriorations were observed as discoloration, wrinkling, and oozing, and major deteriorations were shrinking, peeling, delamination, and cracking. Figure 11 shows the deterioration of one of the specimens with clamping, and 2 continuous wraps of duct tape.

After the first month of aging at 200±°5F (93±3°C), all 18 specimens showed the following deterioration, increasing with time:

- shrinkage and delamination among the unclamped specimens (Figure 12)
- oozing of the adhesive layer in the foil-butyl tape (Tape 4) specimens (Figure 13)
- little shrinkage and delamination in the strapped specimens
- discoloration of the plastic strapping in the clamped specimens

The discoloration of the plastic strapping was an indication of its deterioration which basically lead to a total failure afterward in one case (specimen S7014) after four months of aging The plastic clamp cracked open due to the increased brittleness of the plastic (Figure 14).

Figure 11. Deterioration of flexible duct core-to-sheet metal collar joint during the six months of the aging test.

Figure 12. Shrinkage and delamination among the unclamped specimens (after 5 months of aging)

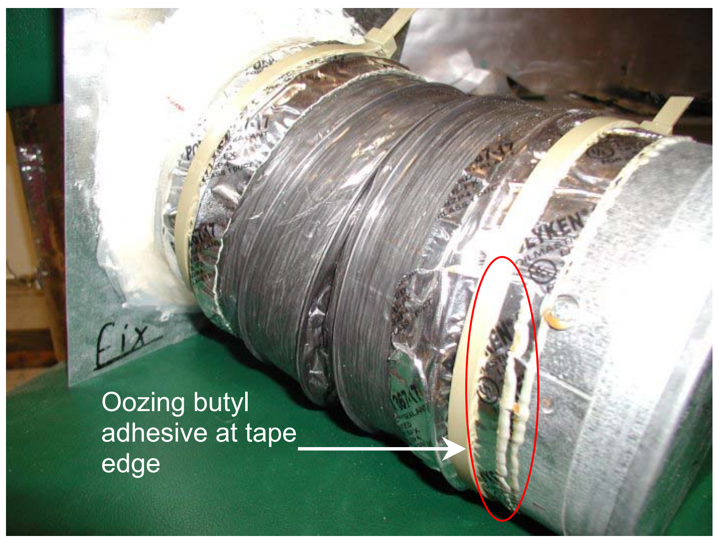

Figure 13. Oozing of the adhesive layer in the foil-butyl tape (Tape 4) specimens (showing result of 5 months of aging).

Figure 14. The failed plastic strapping on one of the flexible core to sheet metal collar specimens after four months of aging.

The leakage results are shown in Figures 15 through 18. From this partial data there are no clear universal trends with both increases and decreases in leakage of different magnitudes for different samples. The cases of decreases in leakage illustrate some of the limitations of our test procedure in terms of the resolution of the leakage tests and other issues, such as the changes due to temperature of the test sample during leakage testing (discussed earlier). For example, for the most recent tests, we waited until the samples were cool before testing, which leads to lower measured leakage. In the earlier measurements we did not consider waiting for temperature stabilization and tested the samples at some intermediate temperature, thus leading to higher measured leakage. The magnitude of the changes in leakage with time and therefore sample temperature shown in Figure 7 indicate that the negative leakage shown in Figures 15 through 18 is of a similar magnitude to this effect. In addition, the visual observations of the core-to-collar joints indicate that that the shrinkage of the duct tape can have a positive effect as it tightens up around the joint, unlike the case of a collar-to-plenum joint where the shrinkage of the duct tape makes it peel off and pull away from the surface it is applied to, thus exposing the leaks.

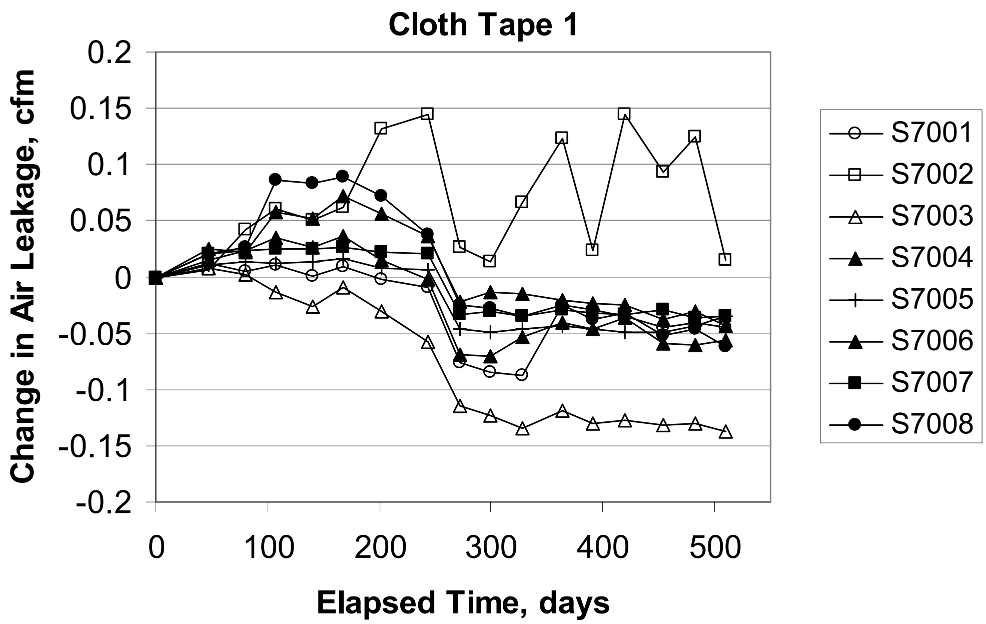

Figure 15. Change in leakage flow of the flexible core to sheet metal collar joint specimens with cloth tape 1.

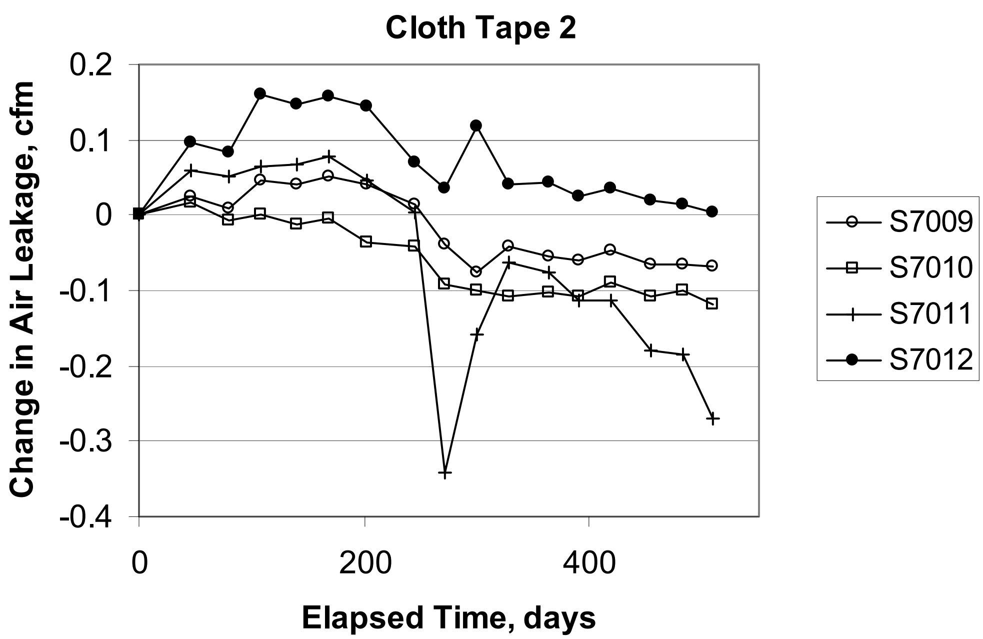

Figure 16. Change in leakage flow of the flexible core to sheet metal collar joint specimens with cloth tape 2.

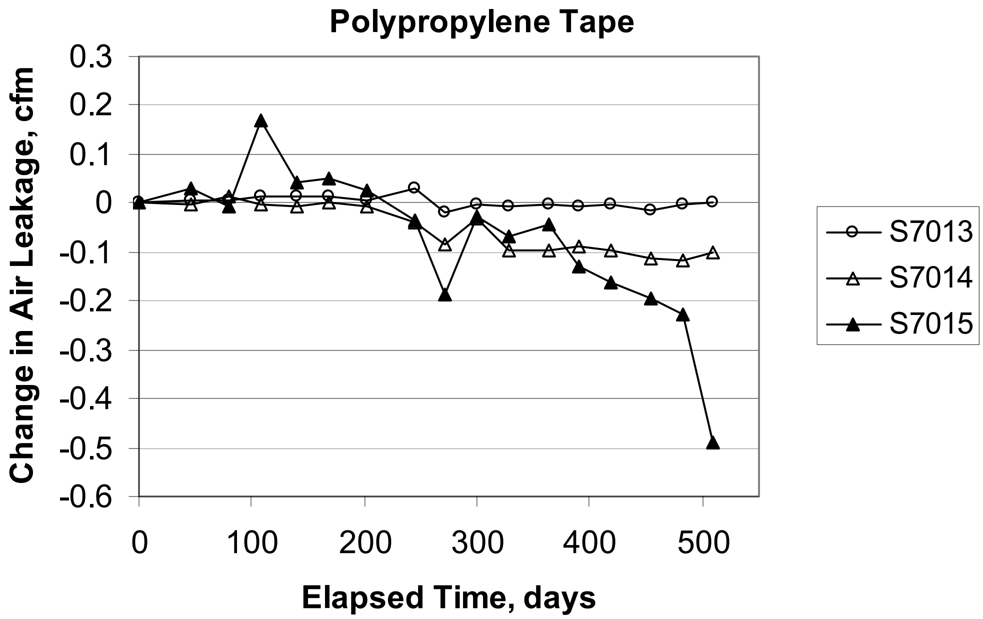

Figure 17. Change in leakage flow of the flexible core to sheet metal collar joint specimens with polypropylene tape 3.

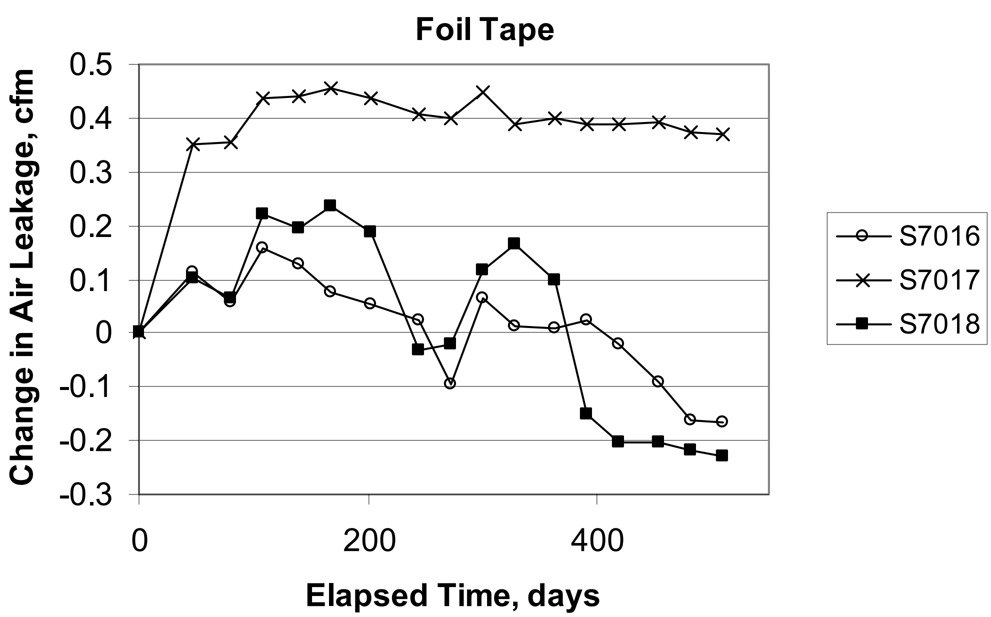

Figure 18. Change in leakage flow of the flexible core to sheet metal collar joint specimens with foil tape 4.

After five hundred days of testing, the flexible duct core-to-collar specimens showed increases in leakage, but no catastrophic failures. However, visual inspection showed the effects of the temperature and pressure during the aging test. The observations as a result of the visual inspection after the six-month period of testing are summarized in Table 3. Table 3 assigns points (0 to 2) to each of the ten features of the degradation; "0" denoting either "no sign of deterioration" in that category (feature), "1" denoting a "moderate deterioration", and "2" denoting an "excessive deterioration". These points are somewhat subjective, but they do serve to give a relative rating for each tape. The table also includes the total number of points given to each specimen. It can be clearly seen that specimens S7013, S7014, and S7015 (all Tape 3, polypropylene tape) showed the most deterioration, while specimen S7009 (Tape 2, duct tape with clamping, two continuous wraps), and specimens S7017 (Tape 4, foil-butyl tape, with clamping, and one discontinuous wrap), and S7018 (Tape 4, foil-butyl tape, without clamping, and one continuous wrap) showed the least deterioration. When the specimens were clamped (S7001, S7002, S7003, and S7004), only the cloth mesh (reinforcement) layer of the tape experienced the shrinkage, whereas in the clamped specimens (S7005, S7006, S7007, and S7008) all layers of the tape experienced the shrinkage.

Table 3. Summary of the Visual Inspection Results of the Flexible Duct Core-to-Sheet Metal Collar Specimens in the Aging Test											
Specimen	Hardening and Brittleness	Peeling	Shrinkage	Wrinkling	Delamination	Flaking	Cracking	Bubbling	Oozing	Discoloration	Total Score
S7001	1	1	1	2	0	0	0	0	0	1	6
S7002	1	1	1	2	0	0	0	0	0	1	6
S7003	2	1	1	2	0	0	0	0	0	1	7
S7004	2	1	1	2	0	0	0	0	0	1	7
S7005	2	0	1	2	2	0	0	0	0	1	8
S7006	2	1	2	2	2	0	0	0	0	1	10
S7007	2	1	2	2	2	0	0	0	0	1	10
S7008	2	1	2	2	2	0	0	0	0	1	10
S7009	2	0	0	1	0	0	0	0	0	0	3
S7010	2	0	0	1	0	0	0	0	1	0	4
S7011	2	0	0	2	0	0	0	0	1	0	5
S7012	2	0	0	2	0	0	0	0	0	1	5
S7013	2	2	0	2	2	2	2	2	0	2	16
S7014	2	2	0	2	2	2	2	2	0	2	16
S7015	2	2	0	2	2	2	2	2	0	2	16
S7016	0	0	0	2	0	0	0	0	2	0	4
S7017	0	0	0	1	0	0	0	0	2	0	3
S7018	0	0	0	1	0	0	0	0	2	0	3

Evaluation of new duct sealant products

Collar-to-plenum testing was performed for a new duct tape product that has been developed to have improved high temperature performance (Tape 5) as well a sample of Tape 1. The new tape was tested on the collar-to-plenum joint in order to facilitate performance comparisons with previously tested duct sealant products. The old tape (Tape 1) new failed in 9 days (using the >10% of unsealed leakage criteria), showing shrinkage and pulling away from the sheet metal plenum. The new tape showed better durability performance failing after about 60 days. Additional tests at lower temperatures showed that the new tape takes longer to fail as temperatures are decreased, and at temperatures below (111°F) 44°C the tape takes more than 100 days to fail (we limited our test duration to 100 days). Figures 19 and 20 show more detailed test results. Because they were mounted in a different location on the test apparatus, these collar-to-plenum were exposed to different temperatures than the core to collar samples. These samples were placed between the left and right chambers (shown in Figure 2) where in previous phases of durability testing the samples experienced cycling temperatures. Table 4 shows the temperatures the specimens were exposed to during the test, and the corresponding elapsed time before failure. Specimen S1102 failed after 2.5 months, and was replaced with specimen S1105. Specimen S1105 appeared to leak at a faster rate at the beginning, then leveled off, then showed a catastrophic (sudden) failure, contrary to the gradual failure of S1002). It took specimen S1105 only one month and three weeks to fail.

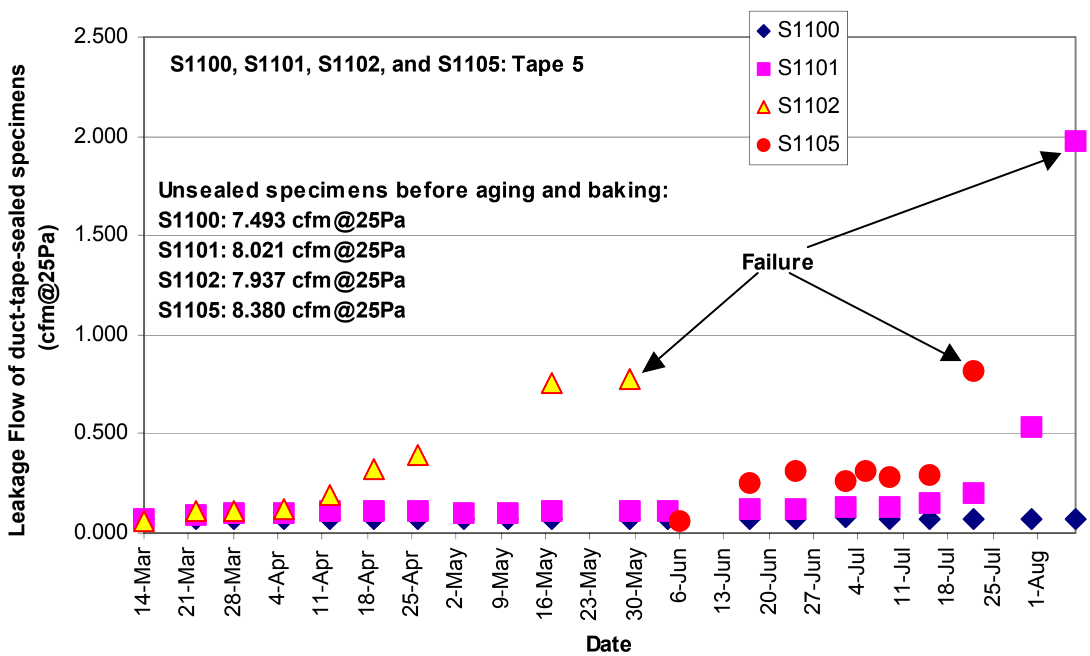

Figure 19. The measured leakage of the collar-to-plenum joint Tape-5 specimens.

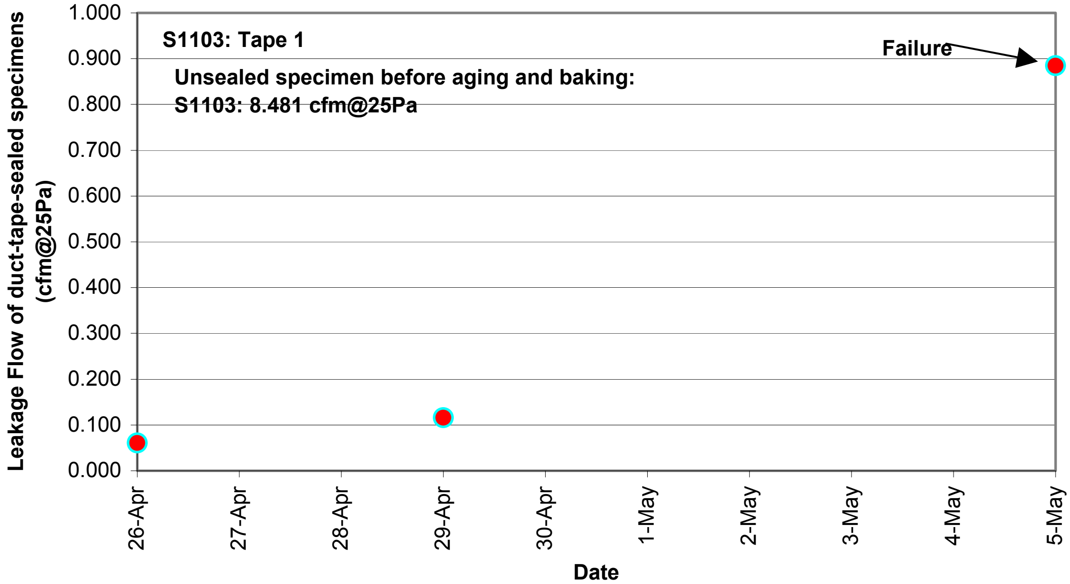

Figure 20. Leakage of the collar-to-plenum joint Tape-1 specimen.

Table 4. Aging Test: Failure Results of the Collar-to-Plenum Joint Specimens			
Tape	**Specimen**	**Temperature F (°C)**	**Elapsed Time Before Failure**
5	S1100	111 (44)	No Failure after 4 Months and 3 Weeks
	S1101	147 (64)	4 Months and 3 Weeks
	S1102	194 (90)	2 Months and 2 Weeks
	S1105	194 (90)	1 Month and 3 Weeks
1	S1103	194 (90)	9 Days

Figure 21 shows the failure of the joint as the duct tape tends to pull away from the sheet metal, thus uncovering the series of overlapping fin-joints.

Figure 21. Example failures of the collar-to-plenum joint.

Developing a standardized test method for evaluating duct sealant durability

Technical development of a draft ASTM standard included changes to test procedures to use single heating only (earlier drafts had both heating and cooling of samples), and an increase in test temperatures. The change to heating only was made in order to make the testing simpler (cooling added significant cost and complexity to the testing). The increase in temperatures was to bring the durability testing more in-line with the existing UL 181B-FX temperature test and comments received on the previous draft from ASTM ballots. Administrative tasks included preparation of drafts, preparation of supporting materials for ASTM ballots, preparing responses to comments received from the ASTM ballot process, and interactions with ASTM staff and other task group members.

Baking test results: Evaluating the UL 181B-FX temperature test

Visual inspection of the baking specimens showed gradual deterioration in the specimens over the 60 days period of the test (as required by the UL standard), whereas specimens of the duct tape tested which were hung in the oven without being applied to any substrate showed considerable deterioration after only two weeks of baking.

After the first week of baking, the specimens showed the following:

- No significant deterioration among all specimens.
- No noticeable shrinkage of the tape on the sheet metal substrates.
- The Aluminum Foil and PET specimens tended to roll (curl).
- The hanging specimens tended to "curl" as well.
- The Polyethylene specimens did not show any rolling; their surface in fact became "rougher" (the polyurethane used is a "woven film").

The rolling in most cases was a result of shrinkage in the duct tape that allows it to deform the substrate with it as it shrinks. In the case of the polyethylene substrates, the substrate itself showed some shrinkage after the second week of baking.

The specimens were inspected weekly. When the test was completed after the 60-day period, the final observations of the visual inspection were recorded and summarized. Table 5 shows these final observations, and, similar to Table 3, assigns points (0 to 2) to each of the ten features of the degradation; “0” denoting either “no sign of deterioration” in that category (feature), “1” denoting a “moderate deterioration”, and “2” denoting an “excessive deterioration”. The table also includes the total number of points given to each specimen.

As can be seen in Table 5, the Tape 4 specimens (foil-butyl tape) showed the least deterioration, while its combination with the sheet metal (SM) substrate shows no deterioration at all. The Tape 3 specimens (OPP tape) showed the most deterioration. Its combination with the aluminum foil (AF) substrate was the worst case. Also, in agreement with the aging test results of the conventional duct tape (Tape 1 and Tape 2), Tape 2 showed a better performance than Tape 1. The results for the hanging specimens were consistent with those of the substrate combinations. The tapes were ranked from worst to best as follows: Tape 4; Tape 2; Tape 1; Tape 3.

All the samples except foil tape showed significant visual degradation in the baking tests and therefore they failed this test. In the future we need to find out how these tapes are able to achieve the UL listing with such obvious failures.

Table 5. Summary of the Visual Inspection Results of the 1-D Specimens in the Baking Test.

Specimen[a, b]	Hardening and Brittleness	Peeling	Shrinkage – Substrate	Shrinkage - Tape	Shrinkage - Both	Wrinkling	Rolling	Delamination	Flaking	Cracking	Bubbling	Oozing	Discolo-ration	Total Score
SM-Tape 1	0	1	0	1	0	2	0	1	0	0	0	0	0	5
SM-Tape 2	1	0	0	1	0	1	0	0	0	0	0	0	0	3
SM-Tape 3	0	0	0	0	0	0	0	1	1	0	0	0	1	3
SM-Tape 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PET-Tape 1	2	0	0	1	0	1	1	1	0	0	0	0	0	6
PET-Tape 2	2	0	0	2	0	0	2	0	0	0	0	0	0	6
PET-Tape 3	1	0	0	0	0	0	2	2	2	2	2	0	1	12
PET-Tape 4	0	0	1	0	0	0	0	0	0	0	0	1	0	2
POLY-Tape 1	2	1	1	0	0	2	0	1	0	0	0	0	0	7
POLY-Tape 2	2	0	1	0	0	2	0	0	0	0	0	0	0	5
POLY-Tape 3	1	2	2	2	2	2	1	0	0	0	0	0	1	13
POLY-Tape 4	0	0	2	0	0	0	0	0	0	0	0	1	0	3
AF-Tape 1	2	2	0	2	0	1	2	2	0	0	0	0	0	11
AF-Tape 2	2	0	0	2	0	1	2	0	0	0	0	0	0	7
AF-Tape 3	2	0	0	0	0	2	2	2	2	2	2	0	2	16
AF-Tape 4	0	0	1	0	0	0	0	0	0	0	0	1	0	2
H-T –Tape 1	2	n/a	n/a	n/a	n/a	2	1	1	0	0	0	2	0	8
H-T – Tape 2	2	n/a	n/a	n/a	n/a	2	2	0	0	0	0	0	0	6
H-T –Tape 3	2	n/a	n/a	n/a	n/a	2	2	0	0	2	0	0	2	10
H-T – tape 4	0	n/a	n/a	n/a	n/a	0	1	0	0	0	0	0	0	1

[a] Substrate material:

SM: Sheet metal; PET: Polyethylene Terephthalate, POLY: Polyethylene, and AF: Aluminum Foil

[b] H: Tape Hanging without substrate.

Conclusions and Recommendations

The test results are summarized in Table 6. The core-to-collar tests are not complete and firm conclusions cannot be drawn until the aging tests have been finalized in the next phase of testing. Although the core-to-collar connections had no significant failures in terms of leakage some samples showed significant visual degradation.

A surprising result was that almost all the clamps used in our testing failed during the 500 days of testing. They all failed in the same way – becoming discolored and brittle and finally falling off the samples. For this reason we recommend either requiring metal clamps or we need to test a wider range of clamps to determine if some materials perform better than others. Given that clamps are required as part of a UL181B-FX sealing system, this failure of clamps is a very important issue. It should be noted that the UL181B-FX system requires the use of clamps but does not test them or have any other performance requirements for the clamps. This significantly reduces the utility of specifying a UL 181B-FX listing in a building code as a method of ensuring acceptable performance.

The two tapes (including a new tape developed specifically for this application) tested on the "collar-to-plenum" connection failed over a range of a few days to about four months. This is similar performance to previous testing by LBNL. The only cloth tape using butyl rubber we tested performed substantially better than other cloth tapes, but not as well as all other tapes or mastic.

All the samples except foil tape showed significant visual degradation in the baking tests and therefore they failed this test. In the future we need to find out how these tapes are able to achieve the UL listing with such obvious failures.

The benefits to California of the work in this study are:

- We contributed to the retaining of existing code language restricting the use of duct tapes. This helps to ensure that new duct systems will not have substantial increases in leakage as they age, thus reducing the future energy use and peak power liabilities for the state, as well as ensuring continued energy cost savings for consumers.

- When the ASTM standard is completed the CEC (and other building code authorities) will have a standard that they can refer to directly to ensure the durability of duct sealants in California buildings.

- Development of improved duct sealants that can be used in California buildings.

- Knowledge of this work in the building industry is raising awareness of duct sealing issues and is leading to tighter duct systems being installed in California buildings, as well as ensuring that these tight systems remain so in the future.

Table 6. Summary of study results			
Product	Test 1: Aging Test		Test 2: Baking Test
	Core-to-collar	Collar-to-plenum	Fail
Tape 1 Cloth-natural rubber adhesive	Tests incomplete	Fail	Fail
Tape 2 Cloth-natural rubber adhesive	Tests incomplete	N/a	Fail
Tape 3 OPP	Tests incomplete	N/a	Fail
Tape 4 Foil-butyl adhesive	Tests incomplete	N/a	Pass
Tape 5 Cloth-butyl adhesive	Tests incomplete	Fail	Fail

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