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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

A metallurgical evaluation was conducted to evaluate the degree of degradation of type 430 stainless steel in woodburning stove flue gas environments. Sections of metallic chimneys that had been used for extended time periods or that had been involved in chimney fires were evaluated.

DISCLAIMER

INTRODUCTION

Background: Metallic chimneys used for wood burning stoves have recently been found by the U. S. Consumer Product Safety Commision (CPSC) to be associated with numerous house fires. These chimneys are currently constructed according to the voluntary standards of Underwriters Laboratory (UL) designated UL103 or UL103HT. The chimneys are designed either as the double walled fiberglass insulated type or triple walled air-cooled type.

To determine the cause of the house fires associated with the metallic chimneys, the Consumer Product Safety Commission has conducted fire investigations throughout the United States. In the course of these investigations, selected chimneys were removed from service for laboratory evaluation. The objective of this laboratory evaluation was to determine the extent to which premature degradation of the material may have contributed to the failure of the chimney and resulted in the fire.

Present Investigation: This investigation was primarily aimed at determining if there was any significant degradation in the materials of construction used in the chimneys during normal long-term operation or as a result of any chimney fires. For the investigation reported here, chimneys manufactured from type 430 stainless steel were evaluated to determine if significant changes occurred in the microstructure or in the mechanical properties of the stainless steel. Selected chimneys were obtained for evaluation after normal extended use and after being involved in chimney fires. Both chimneys of double walled and of triple walled design were obtained for evaluation. For comparison, samples of type 430 stainless steel were obtained for evaluation both in the new, unused condition and after being heat treated in the laboratory for a limited time to attempt to cause metallurgical changes that may lead to embrittlement. Of particular concern was the possibility that long term exposure to the flue gas environment and temperatures could cause embrittlement of the flue liner.

EXPERIMENTAL PROCEDURES

Materials Examined: Sample coupons of type 430 stainless steel were cut from a new, unused chimney to establish reference mechanical properties and microstructures of typical 430 stainless steel prior to exposure to elevated temperatures in a chimney. These samples were annealed type 430 stainless steel in the form of 0.013-inch thick sheets. Additional sample coupons of this new, unused type 430 stainless steel were heated in a chimney heated with propane flue gas to simulate a thermal cycle that could be expected to artificially embrittle the stainless steel. The temperature cycle was controlled to create a time-temperature cycle of 1 hour at 800°F followed by 1 hour each at 850°F, 900°F, 950°F and 1 hour additional each at 900°F, 850°F, and 800°F. Microstructural examination and mechanical properties tests were then performed on these samples after the embrittlement cycle.

Sections from eight chimneys that had experienced chimney fires were obtained. A total of 20 individual chimney sections were obtained for evaluation. Three of these chimneys were of a double walled, fiberglass insulated design and the other five were of a triple walled air cooled design. Single sections were obtained from 10 chimneys that were removed from service after extended service but which had not been reported to have experienced chimney fires. These were evaluated to determine if any change in the microstructure or degradation of the mechanical properties had occurred during normal extended use.

Metallographic Examination: Specimens were taken from all of the type 430 sample coupons and from selected areas of the inner flue liner of each section of every chimney section removed from service for this study. Metallographic specimens were mounted so that the general microstructure could be examined and additional samples were mounted so that the microstructure in the through thickness direction could be examined. Optical metallographic examination, primarily at a magnification of 500X, with selected examinations at magnifications up to 1900X was performed after after polishing and etching. To examine the general microstructure, the specimens were normally etched with glyceregia (20 ml HCl/5mlHNOs/20ml glycerin). This etch was used to show the grain size and the principal microconstituents which were mostly ferrite and iron carbides. In addition, selected specimens were etched with Murakami's reagent, or aqua regia, or 30 ml lactic acid/ 10ml HNO_3/5ml HF to attempt to identify any other microconstituents.

Mechanical Properties Tests: Tensile tests were taken from each sample coupon and from most sections of each chimney. Tests were conducted following the procedures given in ASTM standard test method E8-81 for Tension Testing of Metallic Materials (1). The tensile test specimens had a gage section of 0.5-inch wide by 2.0-inches long and were the thickness of the sample coupons or chimney section (0.010 to 0.018-inch.) Three or more tensile test specimens were taken from each chimney section tested. The 0.2% offset yield strength, ultimate tensile strength and percent elongation to fracture were determined at room temperature for each test specimen.

EXPERIMENTAL RESULTS

Evaluation of "As-Received" and "Embrittled" 430: The type 430 stainless steel examined in the "as-received" condition, which came from a sample coupon cut from a new, unused chimney section, had a microstructure consisting of ferrite grains with carbides randomly distributed throughout the ferrite grains as shown in Figure 1. This microstructure is typical of the microstructure expected for annealed type 430 stainless steel. It is expected that this type of microstructure existed in all of the chimney sections prior to their extended use in chimneys and exposure to high temperature flue gases during normal chimney operation or during chimney fires. The results of the mechanical properties tests are shown in Table I. The as-received type 430 had a tensile strength of 75.8 ksi, a yield strength of 50.6 ksi, and an elongation of 24.7 percent. These values all exceed the values of 65 ksi, 30 ksi, and 20 percent, respectively, specified as minimum values for type 430 sheet material (less than 0.050-inch thick) given by ASTM Standard A176-81 for Stainless and Heat Resisting Chromium Steel Plate, Sheet and Strip.

Sample coupons of type 430 stainless steel which were exposed to the temperature cycle described earlier, that was expected to cause embrittlement showed a microstructure essentially identical to the microstructure of the "as-received" type 430 shown in Figure 1. The microstructure consisted of random carbides distributed within essentially equiaxed grains of ferrite which is typical of annealed type 430 stainless steel. No difference in the microstructure was found by optical metallographic techniques after the embrittlement heating cycle. As shown in Table I, the mechanical properties, of type 430 stainless steel after being subjected to the embrittlement cycle were a tensile strength of 76.8 ksi, a yield strength of 53.4 ksi, and an elongation of 22.4 percent. These values are all above the minimum values for type 430 stainless steel sheet material given by ASTM Standard A176 and are all within the expected typical range for annealed type 430 stainless steel. The elongation values were essentially unchanged by the embrittlement heating cycle. This indicates that this embrittlement cycle was not sufficiently long to cause any significant embrittlement as measured by the elongation to fracture. It is likely that if the type 430 stainless steel is subject to embrittlement, in the temperature range of 800 to 1000°F as measured by the percent elongation to fracture, that considerably longer time periods, in the order of several hundred hours are required.

Evaluation of Chimneys Removed From Service After Being Involved in Fires: The eight chimneys that were involved in fires were examined and are described individually in detail below. Information was obtained about each chimney from the CPSC Investigative Report or brief Collection Report, from visual observations of the inner flue liner after dismantling each chimney section, and from the metallographic and mechanical properties tests performed on the inner flue liner. The identification and brief description of each chimney is given in Table II.

Chimney No. F-815-3683

Description of chimney samples:

Two sections each 36-inches long were removed from the chimney following a chimney fire. Section A was from the attic area where the fire started and section B was the top section of the chimney, above section A, and extended above the roof of the house. The chimney was a double walled, insulated design made made from type 430 stainless steel. Only the inner liner was examined visually and evaluated metallographically and mechanically.

The CPSC investigation report for this chimney indicated that it is likely that this chimney was exposed to high flue gas temperatures during use because the installation included large sized flues, and undersized hot air ducts. In addition a barometric damper was not used for control and very dry oak was used as fuel which can contribute to high flue gas temperatures.

Visual Observations of the inner liner:

In section A, the longitudinal seam showed buckling (approximately 1-inch deep) due to excessive thermal expansion over nearly the entire length of the section. The longitudinal seam had split and opened up for approximately 18-inches in the center of the chimney section, as shown in Figure 2, The center part (approximately 12-inches) of the chimney section showed circumferential blisters about 1/2 inch deep by 1 inch long most of the way around the section, Fig. 3. Slight buckling was found in the circumferential direction at one of the joint ends of the section, Fig. 4. The inside of the inner liner showed no deposits of combustion products and the outside of the liner showed remnants of adherent insulation materials. The inner liner was light brown to slightly blue in color, indicating some heat tinting due to use. The buckling and blisters in this section indicate local heating due to the fire sufficient to cause significant thermal stresses and to reduce the strength of the metal while heated to permit substantial deformation. The opening of the longitudinal seam would prevent the fire from being contained within the inner liner of the chimney.

In section B, the longitudinal seam was split open for nearly the entire length of the section. No evidence of blistering was found in this section. Severe circumferential buckling was observed at the male joint end of the section and heat tinting to a dark blue color was found at the opposite end of this section, Fig. 5. Deposits of rust were found on the exterior surface of this inner liner. No significant deposits of combustion products were found inside this section and remnants of insulation were found on the outside. These observations indicate that this section of the chimney was heated sufficiently to cause buckling due to thermal expansion but that the section was not heated sufficiently to cause sufficient loss of strength of the metal to cause blistering.

Metallographic Examination:

Specimens were taken for optical metallographic examination from several locations in chimney section A and B. All specimens were etched with glyceregia (20 ml HCl-20 ml glycerine-5 ml HNO_3). The microstructure consisted of relatively small equiaxed grains of ferrite with a random distribution of carbides within the grains as shown in Figure 6. Limited amounts of a rough appearing textured "transition" phase which was not identified were observed. This microstructure is typical of annealed type 430 stainless steel. No definitive evidence of alteration to the microstructure due to the fire or exposure to the flue gas was found. The inside surface of the inner liner did show evidence of slight, intergranular oxidation to a depth of approximately one grain diameter.

Mechanical Properties Evaluation:

Tensile test specimens were taken from chimney section A and the ultimate tensile strength, 0.2% offset yield strength, and percent elongation to fracture were determined. The yield strength of 36.1 ksi and the tensile strength of 73.5 ksi were within the typical range of properties for annealed type 430 stainless steel, as shown in Table I. The percent elongation to fracture was 18.7% which is slightly below the range of 20 to 35% which is typical for annealed type 430 stainless steel and is slightly below the minimum value of 20% required by ASTM standard A176. This would indicate the likehood that embrittlement or some reduction in ductility occurred during operation of the chimney or as a result of the fire. However, it should be noted that even this reduced ductility was not sufficient to result in cracking even under conditions of fairly severe deformation that occurred in the longitudinal seam buckling, in the blisters, and in the circumferential buckling at the chimney section joints.

Summary:

Excessive temperatures resulted in buckling and blistering of the chimney section but did not cause microstructural changes that could be found by optical microscopy. The excessive temperature appears to have slightly reduced the ductility of the stainless steel but the failure of the chimney could not be positively attributed to the reduced ductility.

Chimney No. F-815-3685

Description of Chimney Sample:

A single, 30-inch long section of a chimney was obtained, disassembled, and the inner liner was examined for damage caused by a series of chimney fires. The chimney was a double walled, insulated design. The CPSC investigative report for this chimney indicated that large amounts of creosote frequently built up during use of this chimney and that several chimney fires, all contained within the chimney, had occurred during the three years the chimney had been in use. The section used for this examination was from the lowest part of the chimney just above the connection to the smoke pipe coming from the wood stove in the basement of the house. The CPSC report suggested that the possible cause of the excessive creosote formation in this chimney was an excessively large stove and inadequate draft in the chimney.

Visual Observations of the inner liner:

The longitudinal seam of the inner liner was split open for nearly the entire length of the chimney section, Fig. 7. Slight heat tinting on the outside of the inner liner near the openings in the longitudinal seam indicates that the fire may not have been contained within the inner liner at all times.

Severe bending and circumferential buckling was observed at one end of the section, Figure 8, and small cracks were found under microscopic examination of the end of this section. Heavy, adherent deposits of creosote were found on the inside of the liner section. Heat tinting to a light brown color was found throughout the chimney section but no severe "hot spots", such as oxide scale, were found. The split longitudinal seam and buckled joint end of this liner indicate that significant thermal expansion and stresses occurred during the operation of this chimney.

Metallographic Examination:

Specimens were taken for optical metallographic examination from several locations in this chimney section. All specimens were etched with glyceregia. The microstructure shown in Figure 9 shows ferrite grams with extensive amounts of a "transition" phase which was not positively identified. Few carbides were found in this microstructure. Very slight grain boundary attack was observed at the surface of the inner liner, as shown in Figure 10. These microstructural features indicate that some changes in the microstructure had probably occurred during the operation of this chimney due to the frequent overheating during chimney fires.

Mechanical Properties Evaluation:

Tensile test specimens were taken from the inner liner of the chimney section. As shown in Table I the 0.2% offset yield strength was 53.4 ksi, the tensile strength was 99.0 ksi, and the elongation to fracture was 12.4 percent. A tensile strength of 99.0 ksi is substantially above the typical range of 60 to 85 ksi expected for type 430 stainless steel in the annealed condition and the elongation to fracture of 12.4% is significantly below the minimum of 20% specified for this steel in ASTM Standards A176. These results indicate that this chimney was substantially strengthened and embrittled during operation as a result of the frequent overheating due to contained chimney fires. Although the ductility was still sufficient to permit some deformation and buckling of the inner liner without cracking, the low ductility did lead to some small amount of cracking at the joint in one end of the chimney.

Summary:

This chimney section did experience some embrittlement and degradation of properties due to overheating resulting from contained chimney fires. The excessive temperatures also resulted in deformation, buckling, and cracking due to stresses caused by thermal expansion.

Chimney No. F-820-5671

Description of Chimney Samples:

Three sections, two 30 - inch long sections and one "T" section were obtained, disassembled, and the inner liners were examined for damage resulting from a chimney fire. The chimney was a double-walled solid packed design with the inner liner made form type 430 stainless steel. The CPSC investigative report indicated that the fire had started as a result of the ignition of creosote that had built up in the chimney. For some unspecified time just prior to the fire, scrap maple wood covered with varnish had been used as fuel. All sections of the chimney were buckled and showed signs of rust. The "T" section was heavily buckled and completely corroded through in two areas. The buckling of the chimney sections allowed insulation to leak from the bottom of the chimney sections.

Visual Observation of the inner liner:

The two, 30 inch long, straight chimney sections coded A and B both showed buckling and opening of the longitudinal seam indicating substantial deformation due to thermal stresses caused by the fire. Both sections A and B showed rust on the exterior of the inner liner along the seam and near each end of the section. The inside of the inner liner showed some uniform rusting but did not contain significant deposits of combustion products when received for examination. Heat tinting to a light brown color was observed on both section A and B.

Section C, which is the "T" section, was heavily rusted and at two locations was completely rusted or burned through. Heavy oxide scale was observed on this section. The "T" section was located at the base of the chimney near where the connection to the wood stove was made and where the fire was believed to have started. The inside of this section contained thin deposits of combustion products and rust. The vertical seam in this section was open at the time the section was received for examination. The heat tinting and oxide scale on this section indicated that the metal was most likely overheated to a substantial temperature during the fire.

Metallographic Examination:

Specimens were taken from several locations in each of the three sections of this chimney and were examined by optical metallography after etching with glyceregia, For specimens from the straight chimney sections (sections A and B), the microstructure consisted of small grains of ferrite with random carbides uniformly distributed throughout the grains, as shown in Fig. 11. This microstructure is similiar to the microstructure found in chimney number F-815-3683-A (Fig. 6) and is typical of the microstructure found in annealed type 430 (ferrite) stainless steel. This microstructure suggests that these chimney sections were not heated to a sufficiently high temperature for a long enough time to cause significant microstructural changes as a result of the chimney fire. As shown in Fig. 11, grain boundary attack, probably oxidation, occurred at the inside surface of this chimney section to a depth of about one grain diameter.

The "T" section, designated section C, was observed visually to have evidence of being heated to significantly higher than the normal operating temperature as a result of the chimney fire. The microstructure of specimens taken from this chimney section, as shown in Fig. 12, has been altered significantly from the microstructure in sections A and B and is not similiar to "as received", type 430 stainless steel. Few carbides are observed within the grains and substantial areas of a rough appearing transition microconstituent, which has not been identified, are found. This indicated that the "T" section probably was heated sufficiently high enough during the fire to cause some significant change in the microstructure. Metallographic specimens taken near the region where holes were corroded or burned through this chimney section showed deep surface oxidation along the grain boundaries to a depth of several grain diameters, as shown in Fig. 13. This was the most extensive grain boundary attack found in any of the chimney sections examined in this investigation,

Mechanical Properties Evaluation:

Tensile specimens were taken only from section C (the "T" section) of this chimney. This was the section that appeared by visual examination to have experienced the most severe damage by the fire. As shown in Table I, the yield strength of 35.4 ksi and tensile strength of 62.1 ksi were the lowest and the percent elongation to fracture of 30.6 was the highest of any of the chimney sections evaluated in this investigation. Although these properties fall within the typical range for annealed type 430 stainless steel, the tensile strength of 62.1 ksi is slightly below the minimum required to satisfy ASTM Standard A176. These results indicate that this chimney section was heated to a high enough temperature during the fire to completely anneal the metal and remove any strengthening or reduction in ductility caused by cold work during production of the steel.

Summary:

The two straight chimney sections, sections A and B, did not show evidence of microstructural changes resulting from the fire but were damaged by buckling due to excessive stresses caused by thermal expansion. The "T" section of the chimney showed evidence of being severely enough heated to cause changes in the microstructure and mechanical properties and to cause heavy oxidation and burn through to the metal. These results indicate that in a creosote fire, such as experienced in this chimney, the chimney is damaged significantly and the metal degraded to the extent that further use of the chimney is not practical.

Chimney No. F-815-3686

Description of Chimney Sample:

A single, 36-inch long section of the chimney was obtained, disassembled, and the inner liner was examined for damage resulting from a chimney fire. This chimney was a triple-walled, air insulated design with the inner liner made from type 430 stainless steel. The CPSC investigative report showed that there was heavy creosote buildup in the lower two sections of the chimney and that corrosion of the galvanized spacers between the chimney walls and of the chimney walls had occurred. The section examined here is the third or uppermost section of the chimney.

Visual Observations of the inner liner:

When received, the inner liner was extensively deformed and flattened and the longitudinal seam was split open near one end, possibly due to the flattening. It could not be determined if the defomation occurred before or during the fire or if it was a result of dismantling the chimney after the fire. The outside of the inner liner was moderately rusted over its entire surface with more extensive rust near both end joints. No pitting corrosion was found. The only evidence of heating was heat tinting to a light brown color over the entire liner section. The inside of the liner contained powdery deposits of combustion products.

Metallographic Examination:

Specimens were taken from several locations in this chimney section and were examined by optical metallography after etching with glyceregia. The microstructure consisted of small, equiaxed grains of ferrite with finely dispersed carbides throughout the ferrite grains, similiar to the microstructure found in specimens from chimeny number F-815-3683 described above. No evidence of any significant change in the microstructure from that of annealed type 430 stainless steel was found due to the fire. The inside surface of the inner liner showed slight intergranular attack to a depth of less than one grain diameter.

Mechanical Properties Evaluation:

The results of the tensile tests, as shown in Table I, show that the ultimate tensile strength 64.6 ksi, yield strength of 44.5 ksi, and elongation to fracture of 29.6% all are within the expected range of properties typical of annealed type 430 stainless steel. These results indicate that this particular section of the chimney was not exposed to temperatures sufficient to cause any significant degradation of the mechanical properties.

Summary:

The microstructural observations and the mechanical properties tests did not show that this section of chimney had been affected by the chimney operation or by the chimney fire. The deformation of the inner liner could possibly have resulted from corrosion and collapse of the spacer brackets between the chimney walls as was observed by the CPSC investigators.

Chimney No. F-820-1338

Description of Chimney Samples:

Two sections of the chimney were obtained, disassembled, and the inner liners were examined for damage resulting from the chimney fire. The chimney was a triple walled of design made from type 430 stainless steel. The CPSC investigative report noted that some corrosion and detachment of the spacers which supported the middle liner of the chimney pipe had occurred. The inner liner seam was split and soot and creosote were found on the outer surface of the inner liner between the inner wall and middle wall of the chimney. This indicates that the seam had split prior to the fire. Water was reported to have been used directly on the chimney to put out the fire. The chimney appeared to have been subjected to severe heating as indicated by heat tinting to a dark blue color, surface oxidation of the lower chimney section inner liner, and loss of the galvanized pattern on the entire exterior of the chimney.

Visual Observation of the Inner Liner:

Two inner liner sections, one designated A and one designated B, were received for examination. The available information did not permit identification of where each section was located in the chimney relative to the stove, chimney top, or origin of the fire.

The inner liner from section A had a split longitudinal seam throughout most of its length and extensive rust on one end for several inches below the joint. Heavy scaling and blistering were noted on the outside surface of this section, which indicates that this section had been heated to a high enough temperature to cause extensive oxidation and scaling.

The inner liner from section B was rusted at one end and along the longitudinal seam. The longitudinal seam was split for about one-third of its length. One half of the section had been heated sufficiently on one side (approximately a 180° sector) to burn off the paint and cause significant oxidation and scaling. The other half of this section was not heated sufficiently to cause burning of the paint and no oxidation or scaling was observed in this half of section B. The joint at one end of the liner section was circumferentially buckled.

Metallographic Examination:

Specimens were taken from several locations in each of the two sections of the inner liner of this chimney and were examined by optical metallography after etching with glyceregia. The specimen from section A in the region which appeared visually to have been heated excessively in the fire, showed a microstructure consisting of almost all "transition" phase and heavy oxidation at the surface of the inner liner. (See Fig. 14) A specimen from the other end of this section, in a region that was rusted but did not appear to be as severely heated, had a microstructure of moderately large ferrite grains with randomly distributed carbides, similar to annealed type 430 stainless steel.

As shown in Fig. 15, specimens taken from the end of liner section B that did not appear to be over heated had a microstructure consisting of ferrite grains with random carbides similar to the microstructure of annealed type 430 stainless steel. In these specimens, there did not appear to be any significant change in the microstructure that could be attributed to the chimney fire. As seen in Fig. 15, these specimens also showed grain boundary oxidation of the liner surface to a depth of one or two grain diameters. For specimens taken from the end of liner section B that appeared to have been overheated similarly to liner section A, the microstructure consisted of almost all "transition" phase noted before and an absence of random carbides within the grain and appeared similar to that shown in Fig. 14. This confirmed the presence of significant heating and alteration of the microstructure. Heavy oxidation at the grain boundaries to a depth of several grain diameters was also observed in these specimens.

Mechanical Properties Evaluation:

Tensile specimens were taken from both liner section A and the end of liner section B that did not appear to be overheated. As shown in Table I, the specimens from liner section B had an average yield strength of 38.5 ksi, an ultimate tensile strength of 64.3 ksi, and an elongation to fracture of 24.6 percent. These values are all within the normally expected range for annealed type 430 stainless steel and above the minimum value specified by ASTM A176. The tensile specimens from liner section A, which appeared to be overheated, had an average yield strength of 42.5 ksi, or ultimate tensile strength of 82.3 ksi, and an elongation to fracture of 12.1 percent. Although the yield strength and ultimate tensile strength of this liner section A are within the typical range and above the minimums specified by ASTM for annealed 430 stainless steel, they are substantially above the values determined for the same properties for specimens from liner section B. The elongation to fracture of 12.1 percent is substantially below the typical range of 20 to 35 percent and significantly below the minimum specified by ASTM A-176 of 20 percent. These results indicate that liner section A was embrittled, probably as a result of over-heating.

Summary:

This chimney section had deteriorated by rusting for some extended period of time prior to the chimney fire and the longitudinal seam was probably split for some time period prior to the fire as indicated by the creosote and soot on the outer surface of the inner liner. Liner section A was sufficiently heated during the fire to result in substantial oxidation and scaling and to cause embrittlement and some microstructural changes. Liner section B did not appear to have experienced as severe heat damage as liner section A and did not show any significant change in microstructure or mechanical properties when compared with the typical microstructure and mechanical properties of annealed type 430 stainless steel.

Chimney No. F-820-1339

Description of Chimney Samples:

Two sections of the chimney were obtained, disassembled and the inner liners were examined for damage. The chimney was a triple wall design made from type 430 stainless steel. The CPSC investigation reported that the chimney was removed from service because of creosote buildup between the walls of the chimney. The creosote buildup was caused by the use of an improper chimney cap used to prevent downdrafts that allowed flue gases to infiltrate between the chimney walls and cause the deposition of creosote. No actual chimney fire was reported to have occurred prior to the removal of the chimney from service. Heavy soot and creosote deposits between the walls of the chimney sections were found. In addition, smoke stains were noted on the exterior of the chimney at the joint between the upper and lower chimney sections. Two of the four spacer brackets between the chimney walls at the top end of the lower chimney section were detached. No evidence of substantial over-heating was noted, but the exterior and spacers, which were galvanized, were slightly dulled due to the temperatures occurring during operation of the chimney.

Visual Observations of the Inner Liner:

There was no visual evidence of excessive overheating or corrosion on the inner liner of these chimney sections. A thin, light brown, dusty deposit of combustion products was found on both the inside and outside of the inner liner. This confirms the observations noted in the CPSC report that flue gases were not entirely contained within the inner liner. No seam buckling or blistering of the inner liner was found.

Metallurgical Examination:

Specimens were taken from each of the two sections of the inner liner of this chimney, and were examined by optical metallography after etching with glyceria. The specimens from both chimney sections showed a microstructure consisting of equiaxed grains of ferrite with randomly distributed carbides within the grans, representative of annealed type 430 stainless steel. No evidence of any microstructural changes due to operation of the chimney was observed. Metallographic specimens mounted on edge were taken to determine if any surface attack had occurred. No evidence of surface attack by the flue gases was observed by optical metallography at magnifications up to 500X.

Mechanical Properties Evaluation:

Tensile test specimens were taken from each of the two chimney sections received for evaluation. The values reported in Table I are averages for the two sections. Chimney section A (the lower section the chimney) had a yield strength of 53.9 ksi, a tensile strength of 80.1 and an elongation to fracture of 21.4%. Chimney section B (the upper section in the chimney, above the roof) had a yield strength of 40.4 ksi, a tensile strength of 65.1 ksi and an elongation of 28.1%. These values are all within the normally accepted range for annealed type 430 stainless steel and above the minimum value specified by ASTM A176.

Summary:

This chimney did not show evidence of microstructural changes or degradation in the mechanical properties as a result of being used for approximately four years. The microstructure and mechanical properties were representative of those for annealed type 430 stainless steel. The evidence of combustion products on the exterior of the inner liner indicates that some distortion of the inner liner did occur during use and may have been caused by the detachment of the spacer brackets. This suggests that an evaluation should be conducted to determine if the design of this type of chimney is adequate and if the use of galvanized spacer brackets is adequate for preventing distortion of the inner liner during normal operation.

Chimney No. F-820-1241

Description of Chimney Samples:

Six sections of the chimney were obtained, disassembled and the inner liners were examined for damage. The chimney was a triple wall design with the inner liner made from type 430 stainless steel. The CPSC investigative report indicated that nine contained chimney fires had occurred in this chimney over a period of eight years. The fires were extinguished with water sprayed directly on the chimney or by closing off the air supply to the fire. The fires were attributed to heavy buildup of creosote in the chimney. No corrosion, pitting, or other degradation of the chimney was noted and all seams in the inner liner were intact so that no creosote was found between the chimney liner walls.

Visual Observations of the Inner Liner:

Heavy deposits of creosote, up to 1-inch thick, were found on the inside of the inner liner of all chimney sections examined. The outside surface of the inner liner was light dull brown or shiny black in color and did not show any indications of deposits of combustion products. All seams of the inner liner were intact and no evidence of excessive heating was found.

Metallographic Examination:

Specimens were taken from each of the six sections of the inner liner of this chimney and were examined by optical metallography at a magnification of

500X after etching with glyceregia. All specimens examined showed a microstructure of roughly equiaxed grains of ferrite with randomly distributed carbides within the grains typical of annealed type 430 stainless steel as shown in Fig. 16. No evidence of any microstructural changes due to the contained chimney fires or from extinguishing the fires with water was found in any of the chimney sections. As shown in Fig. 16, very slight surface attack, to a depth of less than one grain diameter, was found on the inside surface of the inner liner. This amount of surface attack is probably not significant because it represents the extent of surface attack after eight years of use in the chimney.

Mechanical Properties Evaluation:

Tensile test specimens were taken from three of the six sections of the chimney received for evaluation and represented the upper, center, and lower (nearest the stove) sections of the chimney. No significant differences in the mechanical properties of these three sections were found. As shown in Table 1, for the three sections, the average tensile strength was 76.6 ksi, the average yield strength was 42.0, and the percent elongation of 21.5 percent. All values exceeded the minimum values typical of annealed 430 stainless steel and were above the minimum values to meet ASTM Standard A176.

Summary:

No degradation of mechanical properties and no changes in the microstructure that could be attributed to the operation of this chimney were found. The repeated contained chimney fires that occurred in this chimney can be attributed to the heavy creosote buildup caused by improper operation and/or cleaning of the chimney. The fires did not appear to result in any damage to the chimney or any significant change in the microstructure or mechanical properties of the inner liner.

Chimney No. F-820-1242:

Description of Chimney Samples:

Three sections of the chimney were obtained, disassembled and the inner liners were examined for damage. The chimney was a triple wall design with the inner liner made from type 430 stainless steel. The CPSC investigative report indicated that a contained chimney fire occurred but that it was stopped by shutting off the air supply and that no structural damage to the house occurred. The inside of the inner liner was quite clean with very little cresote deposit present even though the chimney was not reported to have been cleaned during its entire 2 years of use. Further investigation, prior to dismantling the chimney, showed evidence of gross buckling and total separation of one joint and that the inner and middle liners were displaced horizontally by 2 to 3 inches. No pitting, corrosion or evidence of excessive heating was reported.

Visual Observations of the Inner Liner:

The inner liner showed no evidence of high temperature oxidation and all longitudinal seams were completely intact when the chimney sections were received for examination. The chimney sections were clean inside with very light deposits of creosote. No evidence of corrosion damage was found on the inner liners. The outside of all three sections of the inner liner was covered with a thin, adherent, shiny black deposit of combustion products. This indicates that the flue gases did escape from the inner liner and deposit combustion products, probably creosote, between the inner and middle liner of the chimney. This is consistent with the findings in the CPSC investigative report that some buckling and displacement of the inner liner did occur.

Metallographic Examination:

Specimens were taken from each of the three sections of the inner liner and were examined by optical metallography at a magnification of 500X after etching with glyceregia. All specimens examined showed a microstructure of equiaxed ferrite grains with randomly distributed carbides within the grains typical of type 430 stainless steel as shown in Fig. 17. No evidence of any microstrucural changes due to the chimney fire were found in any of the chimney sections, indicating that the temperatures occurring during operation or during the fire were not excessive for this material. No significant surface attack was found on the inside surface of the inner liner.

Mechanical Properties Evaluation:

Tensile test specimens were taken from the inner liner of the upper and lower sections of the chimney. No significant differences in the mechanical properties of these two sections were found. As shown in Table I, the average tensile strength was 76.1 ksi, the average yield strength was 43.9 ksi, and the average percent elongation was 29.2 percent. These values are all well within the typical range expected for annealed type 430 stainless steel and well above the minimum values specified by ASTM standard A176.

Summary:

No evidence of significant changes in the mechanical properties or in the microstructure were found that could be attributed either to operation of the chimney or to the contained chimney fire. The fire appears to have been caused by the ignition of ceosote which had built up in the chimney. Significant buckling and displacement of the inner liner and middle liner did occur due to the fire and/or operation of the chimney which permitted combustion products to infiltrate between the two liners. An evaluation of the design should be conducted to determine if the chimney can withstand the normally expected operating stresses and can tolerate limited exposure to contained chimney fires.

Evaluation of Chimneys Removed from Service After Normal (Non-Fire) Operation: A group of 10 chimneys that had been used in normal operation were obtained, disassembled and the inner liners were examined for damage and for degradation of their microstructure or mechanical properties. These chimneys were not reported to have been exposed to any contained chimney fires or have been involved in any fires resulting in structural damage outside the chimney. The exact history of operation of each of these chimneys, such as the total time that they had been in operation etc., was not known or completely documented. The objective of this limited evaluation was to assess the extent of damage or deterioration occuring in metallic chimneys under normal operating conditions.

The identification of the chimneys and a summary of the results of a visual observation of the inner liner are given in Table III. The mechanical properties measured on specimens taken from the inner liner are shown in Table I. The inner liner of all chimneys examined were made from type 430 stainless steel. The chimneys are identified by the collection report number assigned by the CPSC (i.e. G-810-0767), but for simplicity in this discussion only the last four digits will be used to refer to each chimney (i.e. 0767).

Triple Walled Design Chimneys

From the evaluation conducted here, the seven chimneys identified as being a triple walled, air insulated design, (0767, 0772, 0773, 0774, 0777, 0778, 1216), all appeared to have performed in a similar manner during operation and therefore the results will be discussed first as a common group. It should be emphasized that the exact operating conditions, such a length of total service use, fuel used, type of stove used, cleaning frequency etc. as well as the manufacturer and model number of each of these chimneys were not known.

For the seven triple wall design chimneys, the visual observations of the inner liners did not show any evidence of excessive heating resulting in split seams, blistering or dimpling, or exessive deformation. The only evidence of heating was the oxide coloring on the exterior of the inner liner as a result of normal heating during use. Two of the chimneys, numbers 0767 and 0774, were a light straw-yellow color indicating that they probable had not been exposed to a temperature in excess of about 500°F during operation. The other five chimneys, number 0772, 0773, 0777, 0778, 1216, were blue-purple in color indicating that they were probably heated in a temperature range of 500 to 700°F.

The inside of the inner liners of the triple walled chimneys that were examined contained varying amounts of deposited combustion products, believed to be creosote, when received for examination. The amount of deposited combustion products depends on the fuel used and the exact manner in which the chimney was operated and how recently the chimney was cleaned prior to being removed from service. Three of the chimneys, (numbers 0767, 0778, 1216) had heavy deposits of combustion products that were at least 1/4- inch thick. The other four (numbers 0772, 0773, 0774, 0777) had light (less than 1/8-inch thick to essentially no combustion products) deposited on the inside of the inner liner. No effect of the amount of deposited combustion products on either the microstructure or mechanical properties of the inner liners was found in this investigation. Specimens were removed form the inner liner of these seven chimneys and the deposited combustion products were chemically removed to permit visual examination for general surface attack or pitting. Four of the chimneys (numbers 0767, 0772, 0773, 078) did show some surface pitting type of attack due to corrosion, as shown in Fig. 18. From the through-thickness microstructural specimens, it is estimated that the depth of attack of these specimens was 0.001 to 0.002-inch deep, i.e. approximately 10 percent of the thickness of the inner liner which ranged from 0.011 to 0.018-inch. No surface attack or pitting was found on the inner liner of the other three chimneys that were examined in this group (numbers 0774, 0777, 1216).

The tensile yield strength (0.2% offset) ultimate strength, and percent elongation strength, and percent elongation to fracture were measured on each of the inner liners from the triple wall design chimneys. As shown in Table I, the yield strength of these materials ranged from 40.1 to 51.4 ksi, the ultimate strength ranged from 71.4 to 79.4 ksi, and the percent elongation ranged from 20.2 to 27.5. These values are all within the normally expected range of properties and are all above the minimum values specified in ASTM A176 for annealed type 430 stainless steel sheet material.

Specimens for optical metallographic examination were taken from the inner liners of each of the seven triple walled design chimneys. All specimens were etched with glyceria and examined at magnifications of 500X and 1000X. Specimens from all seven chimneys showed essentially the same microstructure consisting of equiaxed grains of ferrite with random carbides distributed throughout the grains. This structure is typical of annealed type 430 stainless steel. No evidence of any microstructural change due to the operation of these chimneys was found.

In summary, the inner liners from seven chimneys of triple walled design that were examined in this invetigation after what is believed to have been extended periods of normal operation did not show any changes in their microstructure nor any unusual degradation in their mechanical properties. A small amount of surface attack in the form of pitting was found on the inside of the inner liner of four of the seven chimneys but this is not considered to significantly affect the structural integrity of the chimney. No evidence of physical damage, such as seam splitting or buckling, was found on these seven samples.

Double Walled Design Chimneys

Three double walled designed chimneys that had been used in normal operation but which were not reported to have been involved in any chimney fires were obtained for examination. These chimneys were disassembled and the inner liner of each was examined for damage and deterioration. Only a brief collection report was available for chimneys number 5900 and 3680 and therefore the details of the operation and manufacturer and model number were not available for these chimneys. A complete CPSC Investigative Report was available for chimney number 3014. Each of these three chimneys appears to have experienced significantly different operating conditions and degradation during use. Therefore, they will be discussed individually rather than as a group.

Chimney No. F-820-5900:

The inner liner from this chimney was quite clean and free of deposited combustion products when received. No evidence of extreme over heating was observed and the outside of the inner liner was a light yellow-straw color indicating that the inner liner probably was not exposed to a temperature significantly above 500°F for an extended period of time. No evidence of significant surface attack or pitting was found on the inside of the inner liner either visually after cleaning the liner or on examination of the through thickness metallographic specimens at a magnification of 500X. There was evidence of substantial deformation of the inner liner during operation. The longitudinal seam was split open for most of its length and there were numerous circumferential "blisters" present. It is believed that this deformation occurred as a result of heating during normal operation. This deformation and "blistering" was not observed on any other of the "non-fire" chimneys. Such damage suggests that this chimney may have experienced an occasional contained chimney fire that was not detected or reported during its normal operation.

The mechanical properties of this inner liner were not determined because the extensive blistering made it impossible to obtain suitable specimens. Specimens were taken for optical metallographic examination. After etching with glyceregia and examining at magnifications of 500X and 1000X, the microstructure was found to consist of ferrite grains with carbides randomly distributed throughout the grains. This microstructure is typical of the microstructure of annealed type 430 stainless steel. No evidence of any change in the microstructure due to the operation of this chimney was found.

In summary, this chimney appeared to have experienced some structural damage during its normal operation that resulted in blistering and seam splitting. No evidence of degradation in the material was found. The design of this chimney should be evaluated to determine if it is adequate to withstand the normal operating conditions without structural damage.

Chimney No. G-805-3014:

The upper two sections of a five section chimney were obtained, disassembled, and the inner liners were examined for damage. The chimney was a double walled, insulated design with the inner liner made from type 430 stainless steel. According to the CPSC investigative report, the chimney had been used with a coal stove for 4 years before being removed from service. No fire occurred in this chimney but it was removed from service because extensive corrosion of the inner liner was observed during cleaning of the chimney prior to the heating season. The inner liner of the upper two chimney sections was corroded through and the insulating filler material was exposed. No corrosion was observed on the lower three chimney sections and they were not removed from service. The inner liners obtained for evaluation were totally corroded, as shown in Figure 19, and about half of the liner was completely missing. No significant combustion products were deposited on the innner liner.

Specimens were taken from each of the two sections of the inner liner and were examined by optical metallography after etching with glyceregia. The microstructure consisted of equiaxed grains of ferrite with randomly distributed carbides within the grains typical of annealed type 430 stainless steel, as shown in Figure 20. The surface of the inner liner was heavily corroded away as shown in Figure 20. No microstructure changes due to overheating or due to normal heating during the period of operation were found on either of the sections examined.

No mechanical properties tests were performed on this chimney because the extensive corrosion did not permit specimens to be obtained from these sections.

In summary, no microstructural changes were found in these chimney sections. Extensive corrosion of the inner liners of the upper two sections of the chimney was found. The extensive corrosion was most likely due to an improperly fitting rain cover that permited excessive water to get into the inner liner and/or water condensing on these inner liner sections. An evaluation of the design of this chimney and rain cap should be conducted to determine if an improved configuration would prevent excessive corrosion from occurring.

<u>Chimney No. F-820-3680</u>:

The inside of the inner liner from this chimney contained an adherent red-brown deposit when received. This deposit appeared to be more likely rust or metal scale than to be from deposited combustion products. The outside of the inner liner was a brown color indicating that the inner liner had probably not been exposed to a temperature above 500°F. Evidence of severe surface attack and extensive pitting were found when the scale on the inside of this inner liner was removed. As shown in Fig. 21, these pits were found to occasionally penetrate through the entire wall thickness of this inner liner.

Specimens were taken for optical metallographic examination and were examined at magnifications of 500X to 1900X after etching with glyceregia, aqua regia, and

Murakami's reagent. The microstructure was found to be equiaxed grains of ferrite with carbides randomly distributed throughout the grains. This microstructure is representative of annealed type 430 stainless steel. No evidence of other microconstituents was found after extensive examination by optical metallography.

Mechanical properties test specimens were taken from the inner liner of this chimney. As shown in Table I, the ultimate tensile strength was 61.2 ksi and the yield strength was 42.2 ksi. These values are within the typical range of values expected for type 430 stainless steel. The measured elongation to fracture for this material was only 9.2 percent and the tensile strength was only 61.2 ksi which is below the minimum value of 20 percent for elongation and 65 ksi for tensile strength, respectively, as required by ASTM Standard A176 for annealed type 430 stainless steel sheet material. Although these low values of elongation and tensile strength may represent some form of embrittlement in this material, the metallographic examination did not show evidence of any microconstituent that would cause any embrittlement. Therefore, it was concluded that the low elongation and tensile strength that were measured were caused by the extensive deep pitting and tiny holes in the liner material caused by the rusting and scaling found on this liner. These deep pits and holes caused premature failure of the tensile test specimens and therefore caused an unusually low elongation to fracture and low tensile strength.

In summary, this chimney did not appear to have been structurally damaged or experience degradation of the microstructure during its normal operation. However, the inner liner of this chimney was severely pitted and scaled during operation. The pits were sufficiently deep in some cases to entirely penetrate the wall of the liner.

CONCLUSIONS

1. In the sections of chimneys examined, which were constructed of type 430 stainless steel, no evidence of microstructural changes or degradation of mechanical properties such as embrittlement, were found after extended periods of normal operation (without a chimney fire).
2. Chimneys can show sufficient corrosion in normal operation (without a chimney fire) that the structural integrity of the chimney is not maintained and the flue gases are not contained within the inner flue liner of the chimney.
3. In chimney sections made from type 430 stainless steel, some microstructural changes can occur and degradation of the mechanical properties in the form of a significant reduction in the percent elongation to fracture due to embrittlement can occur when the chimney is exposed to chimney fires.
4. Even when the mechanical properties of type 304 stainless steel are degraded by embrittlement due to a chimney fire, the chimneys can sustain substantial plastic deformation in the form of buckling and blistering without evidence of catastrophic cracking.
5. Chimneys that are exposed to chimney fires can experience sufficient plastic deformation in the form of buckling so that the structural integrity of the chimney is not maintained and the flue gases are not contained within the inner liner even when the fire is not severe enough to cause any degradation of the microstructure or mechanical properties of the chimney material.

REFERENCES

1. "Standard Methods of Tension Testing of Metallic Materials;" Annual Book of ASTM Standards; ASTM Standard E8-82.
2. "Standard Specification for Stainless and Heat-Resisting Chromium Steel Plate, Sheet, and Strip," Annual Book of ASTM Standards; ASTM Standard A176-82.

TABLE I

TENSILE TEST RESULTS FOR TYPE 430 STAINLESS STEEL CHIMNEYS

Chimney or Material	0.2% Offset Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	% Elongation (in 2-inches)
430 As Rec'd	50.6	75.8	24.7
430 Embrittled**	53.4	76.8	22.4
430 ASTM A176 (min.)	30.0	65.0	20.0
430 Typical Range	35-55	60-85	20-35
FIRE DAMAGED CHIMNEYS			
F-815-3683	36.1	73.5	18.7
F-815-3685	53.4	99.0	12.4
F-820-5671	35.4	62.1	30.6
F-815-3686	44.5	64.6	29.6
F-820-1338-A	42.5	82.3	12.1
1338-B	38.5	64.3	24.6
F-820-1339	46.8	72.6	24.8
F-820-1241	42.0	76.6	21.5
F-820-1242	43.9	76.1	29.2
NON FIRE CHIMNEYS			
G-810-0767	46.7	74.6	20.4
G-810-0772	42.8	75.4	21.6
G-810-0773	41.3	73.0	22.4
G-810-0774	51.4	76.4	25.1
G-810-0777	44.1	74.7	27.1
G-810-0778	40.1	71.4	20.2
F-812-1216	47.4	79.4	27.5
F-820-5900	Mechanical Properties Not Measured---"Blisters"		
F-820-3680	42.2	61.2	9.2
G-805-3014	Mechanical Properties Not Measured--Too Corroded		

Notes:

* Each value represents average of 3 or more tensile tests
** Heated for 2 hours at 800, 850, 900, 950°F

TABLE II

SUMMARY OF RESULTS FOR FIRE DAMAGED CHIMNEYS

Chimney No.	Type (1)	Microstructure (2)	Surface(3) Attack	Mechanical(4) Properties	General Observations (5)
F-815-3686	Triple	F.+C., Ann.	No	Normal	Seam split Extensive deformation Exterior rust Powdery deposit
F-820-1338	Triple	F.+C., Ann.	Yes	A-Low Elon. B-Normal	Seam split Heavy scale on sec. A Exterior rust on sec. B
F-820-1339	Triple	F.+C., Ann.	No	Normal	No physical damage Dusty deposits
F-820-1241	Triple	F.+C., Ann.	Yes (Deep)	Normal	No physical damage Heavy creosote
F-820-1242	Triple	F.+C., Ann.	No	Normal	Buckled Light deposits (Int. + ext.)
F-815-3683	Double	F.+C., Some trans. phase	No	Low Elon.	Seam buckled Blisters Exterior rust
F-815-3685	Double	F.+C. Much Trans. Phase	No	Low Elon. High Tens. Strength	Seam split Blisters Cracks at joint
F-820-5671	Double	F.+C.	Yes (Deep oxide)	Normal	Seam split Buckled Heavy rust/ burn through

Notes:

1. Double or triple wall design

2. F-ferrite C-carbide
   Ann. microstructure typical of annealed type 430
   Transition Phase-unidentified microconstituent; (not F or C)

3. Pitting or surface oxide at grain boundaries

4. Normal-Mechanical properties fall within normally expected range for annealed type 430 stainless steel

5. General condition of inner liner only

TABLE III

SUMMARY OF RESULTS FOR NON-FIRE DAMAGED CHIMNEYS(*)

Chimney No.	Type	Microstructure	Surface Attack	Mechanical Properties	General Observations
G-810-0767	Triple	F.+C., Ann Small grains	Yes	Normal	No physical damage Heavy creosote
G-810-0772	Triple	F.+C., Ann. Small grains	Yes	Normal	No physical damage Thin creosote layer
G-810-0773	Triple	F.+C., Ann.	Yes	Normal	No physical damage Thin creosote layer
G-810-0774	Triple	F.+C., Ann.	No	Normal	No physical damage Thin, tight creosote layer
G-810-0777	Triple	F.+C., Ann.	No	Normal	No physical damage Very clean
G-810-0778	Triple	F.+C., Ann. Large grains	Yes	Normal	No physical damage Very heavy creosote
F-812-1216	Triple	F.+C., Ann.	No	Normal	No physical damage Heavy creosote
F-820-5900	Double	F.+C., Ann.	No	Not Measured	Seam split Blisters Clean-no deposits
F-820-3680	Double	F.+C., Ann.	Yes (Deep pits)	Low Elon. & Tens. strength	Deep corrosion pits-through wall Scaling
G-805-3014	Double	F.+C., Ann.	Yes (Total rust)	Not measured	Heavy rust Parts of inner liner completely missing

* See notes on Table II for explanation of items in this table.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

A metallurgical evaluation was conducted to evaluate the degree of degradation of type 430 stainless steel in woodburning stove flue gas environments. Sections of metallic chimneys that had been used for extended time periods or that had been involved in chimney fires were evaluated.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)
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