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DURABILITY OF STAINLESS STEEL FLUES

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PREFACE

This report on a project carried out at the Building Research Association of New Zealand describes an investigation into the factors which affect durability of stainless steel flues used with solid fuel heating appliances.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the assistance of Dr J.R. Duncan, Messrs. A. Woodside and K. Trotter of BRANZ, and G. McIlhone of Industrial Processing Division, DSIR.

This report is intended primarily for metal flue manufacturers and code writers but parts will be of interest to approving authorities and users of solid fuel installations.

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ABSTRACT

Over recent years the advent of the closed combustion solid-fuel stove in New Zealand has led to an increased usage of metal flues (currently estimated to be about 250,000) and in particular lightweight stainless steel flues. However, it is becoming increasingly apparent that some of these flues are not living up to expectation. Rather than remaining "stainless" some have degraded at an alarming rate, leading to perforation after three to five years of use.

In order to understand some of the factors influencing the early degradation of stainless steel flues, a review of the literature was carried out and this study report discusses the findings. It also summarises the results of a survey of 17 New Zealand metal flue manufacturers to determine the materials, practices and flue designs in current use by the industry. In addition, four case studies of stainless steel flues that had degraded in service are discussed. The report concludes that metal flues for solid-fuel stoves should be made from austenitic stainless steel; that many stainless steel flues are likely to have a limited life span and that regular maintenance and inspection of the installation is essential.

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INTRODUCTION

Over recent years the advent of the closed combustion solid-fuel stove in New Zealand has led to an increased usage of metal flues (currently estimated by the Building Research Association (BRANZ) to be about 250,000) and in particular lightweight stainless steel flues. However, it is becoming increasingly apparent that some of these flues are not living up to expectation. Rather than remaining "stainless", some flues have been observed to degrade at alarming rates, in some cases leading to perforation after three to five years of use.

Where this degradation occurs and remains undetected as it might in an attic roofspace, the home occupant faces a potentially hazardous situation. Hot gases escaping from perforations in a flue can lead to increased heat transfer through the surrounding shield which may eventually ignite adjacent combustible material. At best the flue may need replacement, at worst the entire structure and lives can be put at risk. A schematic of a free-standing solid-fuel installation illustrating its main components is shown in Figure 1.

During the New Zealand winter of 1987, there were five reported domestic fire incidents attributed to flue defects in solid-fuel installations (Woodside, personal communication, 1988). This represents 11% of all reported fire incidents involving solid-fuel stoves. Since a large proportion of stainless steel flues have been installed within the last ten years or so, the Association expects this reported incident rate to increase in years to come as more flues near the end of their useful life. The Association is also concerned that a small number of manufacturers may be using types of stainless steel with less than adequate corrosion resistance.

The objective of this project was to investigate the factors which affect the durability of stainless steel flues, and provide guidelines as to how they should be designed, constructed and used to provide for the safe operation of solid-fuel stoves.

Instances of perforated or failed flues have been identified by the Association and they show a range of degradation problems; from holes appearing in the flue wall to stress cracking and destruction of lock-folded seams. Case studies of four degraded flues, which were the subject of a detailed examination by a Department of Scientific and Industrial Research (DSIR) metallurgist, are discussed later in the report.

SURVEY OF NEW ZEALAND MANUFACTURERS

During the period April to October 1987, an industry survey of metal flue fabricators was undertaken with the objective of gaining an overview of the materials and practices currently used by manufacturers in New Zealand. Most of the respondents were solid-fuel stove manufacturers who also produced their own flue kits, but there were also some heating and ventilating specialists and flue specialists who fabricate flues for the solid-fuel heating industry as part of their operation. Again, the aim of the survey was to gain an overview and was not intended to be exhaustive of every flue manufacturer in the country.

The following questions were asked of the manufacturers:

1. What type of material did they use to fabricate their flues?

2. What was the wall thickness of that material?

3. What was the internal diameter of their flue sections?

4. What method did they use to join sections of flue?

5. How did they fabricate the flue?

6. What was their method of forming the seams?

They were also asked to comment generally on the design and durability of metal flues.

There were 17 respondents to the survey. Of these, all except one used stainless steel AISI (American Iron and Steel Institute) type 304 (austenitic) and the exception used AISI 316 (also austenitic). There was also one other who recommended AISI 316 for coastal applications. In addition, three of the AISI 304 users also produced vitreous enamelled steel flues.

The thickness of stainless steel used was invariably the minimum specified in the standard i.e., 0.6 mm (24 gauge). All respondents used cold rolling to form the flue from sheet material and 12 of the 17 used lock-folding techniques to form the seams; the other four were continuously or spot-welding the seams (although one planned to switch to lock-folding).

In summary, the most popular form of metal flue produced by the 17 surveyed manufacturers was one made of stainless steel AISI type 304, cold rolled and worked with lock-folded longitudinal seams, in prefabricated sections intended to be fitted together when installed on site.

DISCUSSION OF THE LITERATURE

Introduction to Stainless Steels

Stainless steels are those ferrous (iron - Fe) alloys which contain a minimum of 12% chromium (Cr) for corrosion resistance (Fischer and Maciag, 1977). These alloys resist corrosion by forming a passive, protective oxide layer or film over the surface of the steel. For this layer to remain stable and reform spontaneously a minimum of 12% chromium is required. As the amount of chromium in the steel is increased the protective surface layer increases in strength and the corrosion-resistance of the steel improves. Sometimes nickel is also added to impart further corrosion resistance. Small amounts of other minor elements including carbon are also usually present.

The beneficial effect of chromium on the corrosion-resistant properties of steel means that stainless steels are more durable in corrosive environments than mild or carbon steel.

Bukovinsky and Keys (1980), Redmond and Miska (1982), Miller and Boulton (1982) and Boulton and Miller (1986) provide informative introductions to the basics of stainless steels, while Peckner and Bernstein (1977) have compiled a comprehensive overview in their "Handbook of Stainless Steels".

Types of Stainless Steel

There are five basic types of stainless steel: austenitic, ferritic, martensitic, duplex and precipitation-hardening. These terms refer to the different ways that the atoms in the alloy are arranged (i.e., the microstructure). The relationship between the amounts of chromium and nickel for these different types of stainless steel is shown in Figure 2 (from Miller and Boulton, 1982). The martensitic and precipitation-hardening types are heat treatable and should <u>not</u> be considered as flue pipe material. However brief descriptions are included here for the sake of completeness.

<u>Austenitic</u> stainless steels are the most commonly used. They have a face-centred cubic, single-phase structure at room temperature; are able to be hardened and strengthened by cold work (e.g., by bending, rolling or otherwise deforming the steel) but not by applying heat and they are usually non-magnetic but can become slightly magnetic under certain conditions. Stainless steel flues are frequently fabricated from AISI type 304 which contains nominally 18% Cr and 8% Ni as alloys. AISI type 316 is also sometimes used for flues (particularly in the UK). It contains 2% molybdenum for improved corrosion resistance. Both these types are permitted to have a maximum carbon content of 0.08%.

<u>Ferritic</u> stainless steels have a body-centred cubic crystal structure and are magnetic at room temperature (a useful property which distinguishes them from austenitic stainless steels) and like the austenitics these steels cannot be strengthened by heat treatment. The chromium content can vary from approximately 14% to 27%. The ferritic stainless steels suffer from embrittlement at elevated temperatures which has a detrimental effect on their corrosion resistance. AISI type 430 has been used in New Zealand and overseas in the construction of metal flues.

<u>Martensitic</u> stainless steels generally contain 11-18% chromium; have an austenitic structure at elevated temperatures and are able to be hardened by heat treatment. At room temperature they are magnetic and have a martensite microstructure. Redmond and Miska (1982) say: "Martensitic stainless steels are subject to temper brittleness and should not be heat-treated or used in the range of 430°C to 530°C if toughness is important."

<u>Duplex</u> stainless steels have a two-phase structure consisting of austenite and ferrite. They generally contain high levels of chromium and low amounts of nickel. Boulton and Miller (1986) give a maximum recommended service temperature of 300°C because, like the ferritics, they also suffer from embrittlement. While recent developments in Sweden by Sandvik have resulted in a low-cost, highly corrosion-resistant stainless steel (SAF 2304 - said to be superior to AISI type 316) the embrittlement of these duplex stainless steels, in general, at elevated temperatures (>300°C) is still a limiting factor.

<u>Precipitation-hardening</u> stainless steels are chromium-nickel types but also contain other alloying elements such as copper or aluminium. Heat

treatment of the fabricated article is required which can be difficult in the case of metal flues. Precipitation-hardening stainless steels may show thermal instability i.e., increased strength and decreased toughness when held for long periods in the range 315°C to 480°C (Myers, 1977). This also makes them unsuitable as a flue material.

Corrosion and Embrittlement of Ferritic Stainless Steels

Instances of premature degradation of ferritic AISI type 430 stainless steel flues in New Zealand have been noted by the Association. The case studies described later in this report include an AISI type 430 flue which corroded to perforation at a swaged roll after only three years service on a pot-belly stove.

Wood Heating Education & Research Foundation (WHERF, 1987) in the United States report in their study manual that:

> "Some manufacturers of metal chimneys have made available models having inner liners fabricated from Type 304 or Type 316 stainless steel. Most liners were originally Type 430 stainless steel. It was found that Type 430 stainless steel in some cases was susceptible to corrosion damage when used with coal."

The phenomenon of "475°C embrittlement" is well reported in the literature by Demo (1977), Myers (1977), Sedriks (1979) and Moller, Franson and Nichol (1981). It can occur when Cr-Fe alloys containing more than about 12% chromium are heated in the temperature range 340°C to 540°C. The alloy becomes brittle and loses corrosion resistance. The maximum effect occurs at about 475°C (hence the name) and generally, the higher the chromium content the shorter is the period required to develop this embrittlement. Sedriks (1979) describes the most prevalent theory as to how the phenomenon occurs as being the precipitation of a chromium rich alpha prime phase (a chromium carbide) at the grain boundaries. Demo (1977) has reviewed the work of many researchers and says:

> "...alloys with more than about 16% chromium should not be used for extended service between 370 and 540°C, especially if the alloy is cycled from room temperature to the operating temperature during process shutdowns or excursions."
>
> "...cold-work intensifies the rate of 475°C embrittlement. In addition to drastic reduction in toughness and ductility, embrittled Cr-Fe alloys show a severe reduction in corrosion resistance."

The degree of embrittlement depends on the chromium content of the steel and the length of time the alloy is exposed to these temperatures (several hundred hours may be significant). Baylor (1985), while testing for susceptibility for intergranular attack in stainless steels, noted that a 26Cr-1Mo steel showed maximum attack after 500°C heat treatment and minimal attack at other aging temperatures (400°C and 600°C). He attributed the likely reason to be embrittlement, principally near 475°C.

Moller, Franson and Nichol (1981) review the use of ferritic stainless steel as heat exchangers in a number of refineries. They say of these steels;

> "Although the alloys are ductile at the operating temperature, they may be brittle at room temperature. For these reasons, use of these steels in Code applications is limited to 343°C."

The general opinion represented in the literature indicates ferritic stainless steels are not appropriate materials to use in solid fuel stove flues, particularly in light of the temperatures involved. As described later, this critical temperature range of 340°C to 540°C is not untypical at the lower end of such flues. Furthermore, it is also apparent that the martensitic, duplex and precipitation-hardening types of stainless steel suffer from similiar embrittlement effects in a similar temperature range.

Sensitisation of Austenitic Stainless Steels

An alloy is said to be "sensitised" if it is more susceptible to intergranular corrosion than a non-sensitised sample of the same alloy (Povich and Rao, 1978). Atkinson and VanDroffelaar (1982) have made some observations on sensitisation which are:

"(1) Sensitisation occurs when the alloys are slowly heated or cooled through the range of approximately 500°C to 800°C.

(2) Fast cooling through this temperature range does not result in sensitisation.

(3) Quenching from elevated temperatures followed by reheating in the 500°C to 800°C range causes the steel to become sensitised.

(4) The degree of sensitisation increases markedly with increasing carbon content, and to a lesser degree with decreasing chromium content.

(5) The degree of sensitisation varies within the sensitisation temperature range.

(6) The degree of sensitisation also increases with time at the sensitisation temperature.

(7) The prominent feature of sensitised austenitic stainless is the presence of precipitates of chromium carbides at the grain boundaries."

A steel which has been sensitised may appear essentially unaffected, yet it will be found to possess reduced strength and corrosion resistance which, if severe enough, will cause the steel to lose its characteristic metallic ring if struck with a metal object; while bending or twisting will produce cracks (Bain, Aborn and Rutherford, 1933).

The most popular explanation for the sensitisation phenomenon is the chromium depletion theory. According to Miller and Boulton (1982) intergranular corrosion occurs along the grain boundaries of a metal. The mechanism for such an attack is attributed to the loss of chromium near the grain boundaries due to the formation of chromium carbides at the boundaries (see Figures 3a and 3b). A galvanic couple between the chromium depleted zones and the bulk of the grains (Jagannathan et al, 1987) can mean such zones become anodic relative to the rest of the alloy and rapid corrosion due to the combination of electrolytic action and direct attack can then proceed. This topic is also discussed by Novak (1977), Wallen and Ollsen (1977), Bain, Aborn and Rutherford (1933) and Franks (1948).

In particular, Franks (1948) says:

> "...austenitic steels are metallurgically unstable when heated in the temperature range 350°C to 800°C. After heating in this temperature range they become subject to severe attack at the grain boundaries by even relatively mild corrosive media."

Here a range of 350°C to 800°C is stated, which is supported by Scott (1985), but most other literature refers to the 500°C to 800°C range as being critical. The apparent inconsistencies in the literature are due to the fact that sensitisation is a time-dependent reaction. The longer the period of exposure the wider the critical temperature range becomes. The reaction occurs most readily in the 650°C to 700°C range. Time-temperature sensitisation curves for several austenitic stainless steels are shown in Figure 4 (from Scott, 1985). The degree of sensitisation is dependent on carbon content, the time spent in the critical temperature range and other metallurgical factors. Reducing the carbon content in the steel appears to provide some protection against sensitisation during service or welding (and presumably a chimney fire) and according to Scott's work switching from AISI 304 to AISI 316 increases the lower limit of the critical temperature range by about 50°C.

Baylor (1985) concluded, from his testing for sensitisation of various types of stainless steel after heat treatment at 400°C, 500°C and 600°C for 10, 100, 1000 and 5000 hours, that AISI 304 and 321 can be sensitised in 5000 hours at 400°C; or 100 hours at 500°C (also 304L). After 1000 hours at 500°C, AISI 310, 316 and 316L also showed susceptibility but AISI 317, 317L and 347 continued to resist sensitisation past 1000 hours. His recommended maximum temperature for the low carbon types (given the suffix 'L' e.g., 304L) was 450°C.

Baylor's data can be interpreted in the following way. An AISI 304 flue used for about 400 hours per year, and at a temperature of 500°C for 5% of that time (i.e., 20 hours per year) would become fully sensitised after about five years. The flue may still perform its intended function for several more years but its susceptibility to corrosion and failure would have greatly increased.

It has been proposed in recent times by Povich and Rao (1978) that the sensitisation phenomenon has two steps; the nucleation of $Cr_{23}C_6$ (chromium carbide) particles and their subsequent growth. Atkinson and VanDroffelaar (1982) have this to say about the work of Povich and Rao:

> "Povich and Rao have shown that fine carbide particles, visible under the electron microscope, are formed in a few minutes at sensitisation temperatures. These nuclei will grow

> to sizes that confer full sensitisation in 10 days at 400°C or in an estimated 10 years at 300°C. The conclusion that should be drawn from this work is that no standard grades of austenitic stainless steel should be used at temperatures in excess of 300°C if processing (including welding) has led to precipitation of intergranular carbide nuclei."

The implications of welding austenitic stainless steels now become apparent. Higgins (1972) describes the defect known as 'weld decay'. It occurs in regions of the metal, either side of the weld, which have been maintained between 650°C and 800°C long enough for chromium carbide to precipitate there. Factors which determine the degree of sensitisation from welding include the welding technique used, the period of time at a particular temperature and the thickness of the steel (Atkinson and VanDroffelaar, 1982). If stainless steels must be welded and sensitisation is likely, and a stress relieving heat treatment is impractical or uneconomic then low carbon or stabilised grades of stainless steel are usually recommended.

Welding stainless steels can destroy the protective oxide film and alter the microstructure of the metal around the weld. Page (1984) describes some of the hazardous effects of fabrication techniques including welding. In particular, he identifies some of the recent advances which have been made with tungsten inert gas (TIG) welding and metal inert gas (MIG) shielded welding which enable welding to be undertaken with minimal destruction of the oxide film.

Page also says that heating during welding of light-gauge material less than about 3 mm is likely to be of very short endurance and little if any benefit will be gained from using 'L' grades of steel. Referring back to Scott's time-temperature curves (Figure 4), at least seven minutes exposure in the range 650°C to 700°C during welding is required for full sensitisation to occur in AISI 304 (0.06% carbon). However, according to similar time-temperature curves from Bukovinsky and Keys (1980) this steel would require three to four minutes exposure, and the same steel with the maximum 0.08% carbon content would require exposure of less than one minute in the 700°C to 900°C temperature range. On this basis, continous welding of lightweight stainless steel flue seams may be an acceptable fabrication technique but will depend on the precise carbon content of the steel and the rate of cooling achieved in the welding zone.

If metal flue manufacturers are uncertain as to whether their welding process is producing a sensitised microstructure in the steel at the time of fabrication they could have a representative sample of their product (provided it is made from austenitic stainless steel) tested to the American Society for Testing and Materials standard practices for detecting susceptibility to intergranular attack in austenitic stainless steels (ASTM A 262, 1981). Practice A of this standard is the oxalic acid etch test which is used to identify an unacceptable microstructure. If an unacceptable microstructure is found, Practice B, the ferric sulphate - sulphuric acid test, can be used to confirm sensitisation by the presence of chromium carbide. Baylor (1985) provides an interpretation of the corrosion rate determined in Practice B.

The advantage of lock-folding the seams of metal flues is that welding is not necessary and the risk of sensitisation at the time of fabrication is avoided. However the 'cold-working' implicit in the lock-folding technique can cause problems of its own.

The susceptibility of cold worked areas of flues to early degradation has been observed by the Association and is a common feature of the case studies described later in this report. The effect of cold-working on the properties of austenitic stainless steels is discussed in a paper by Bagnoli (1981) investigating the deterioration of austenitic stainless steel refractory anchors which appeared to be related to the cold worked condition of the material when it was subjected to temperatures in the range 538°C to 816°C. The failures he observed were attributed to loss in creep strength, most likely due to the effects of recrystallisation; a mechanical rather than corrosion effect. Based on this work and that of others Bagnoli concluded that:

> "...unrelieved cold work has a serious effect on the elevated temperature creep strength and ambient temperature ductility of most if not all austenitic stainless steels if they are to be exposed to temperatures in the range 538°C to 816°C."

He also recommends that all austenitic material which has been subjected to any degree of cold working and is to be exposed to temperatures above 538°C, be given a solution annealing heat treatment (i.e., be relieved) subsequent to any cold working. This may not always be a practical or economic alternative.

In a recent study by Bose and De (1987) on the influence of cold work on the sensitisation of AISI 304, it was found that the degree of sensitisation increased with increasing cold-work up to about 20% prior cold work (percentage reduction in steel thickness after rolling), but then decreased for deformation levels exceeding 35%. It would appear possible, on the basis of this work, that very heavily cold worked areas may be less susceptible to sensitisation than some areas with a lesser degree of cold work.

Metal Flue Service Temperatures

Measurements of the temperatures likely to be encountered in use on the surface of metal flue pipes connected to several different solid-fuel heating appliances were made by Fox and Whittaker (1955). The maximum temperatures recorded were in the ranges 700°C to 815°C at the appliance outlet and 360°C to 510°C at 1 m from the appliance outlet. These maximum values were obtained by burning coal in the appliances.

In a study of the heating of panels by flue pipes by Lawson, Fox and Webster (1952) it was necessary to determine the surface temperatures of flue pipes. Several tests were carried out with the main objective being to find out the maximum temperatures which can be attained by metal flue pipes joined to domestic heating appliances. An openable coal-fired stove operating with firedoors closed and ashpit door open was selected on the basis that it was most likely to give the highest temperatures when operated under maximum overload conditions. Peak temperatures of over 800°C were recorded. It is unlikely that these peak temperatures would be reached in practice unless one was deliberately trying to do so (as in the tests) and it was not expected that a temperature of 500°C would be exceeded for more than half an hour at a time in practice.

Peacock, Ruiz and Torres-Pereira (1980) reported on a sponsored study by the Center for Fire Research at the National Bureau of Standards investigating the fire safety of wood-burning appliances. Their tests were conducted using five different solid-fuel appliances. Measurements of the flue pipe surface temperatures during steady-state operation ("brand fire test") and overload conditions ("flash fire test") were made. The maximum flue pipe surface temperature for the steady-state tests ranged from 212°C to 456°C (average 375°C) while for the overload tests the range was 417°C to 609°C (average 520°C). They also observed that during the overload tests it was evident that flames extended into the flue pipe from the appliance.

Another study reported by Peacock (1983) into the intensity and duration of chimney fires included several "overfire tests" where the appliances were fired at very high rates with a clean flue for extended periods of time until steady-state conditions were reached. These "overfire tests" produced maximum temperatures in prefabricated, insulated metal chimneys ranging from about 650°C to 850°C at the base of the chimney and 114°C to 775°C at the top.

Further, in a study of the thermal performance of masonry chimneys and fireplaces, Peacock (1987) recorded maximum temperatures of about 350°C on a stainless steel flue liner.

Flue surface temperature measurements were recorded at BRANZ in 1983 on a pot-belly stove (Trotter, personal communication, 1987). Maximum temperatures of about 500°C were recorded on the flue at the appliance outlet reducing to about 440°C at 1 m from the appliance.

During the course of their work, the Coal Research Association of New Zealand have measured temperatures of up to 630°C on the flue skin just above the body of the appliance (Matheson, personal communication, 1987).

The Department of Scientific and Industrial Research (DSIR) made some measurements while testing an alternative chimney construction (Katzer and McAuliffe, 1982). They recorded a maximum of 404°C on a 100 mm diameter flue pipe (with a cast iron stove) at a height of about 460 mm below the ceiling.

It is often difficult to interpret overseas measurements of the temperatures attained on metal flues or chimneys as the design and output of the solid fuel appliance plays an important role. Usually, few details (mostly generic) are given about the appliances used, and how these appliances compare with the closed combustion and pot-belly stoves commonly available in New Zealand is uncertain. Nonetheless, it appears that it is possible to reach temperatures in excess of 400°C on the lower end of a lightweight metal flue under "normal" steady state conditions and temperatures in excess of 600°C if the appliance is operated in an "overfired" manner for a lengthy period of time.

Flue Fires

In light of the previous discussion on sensitisation of austenitic stainless steels it is apparent that sensitisation could conceivably occur during a chimney fire (or during the subsequent cool-down period). Instead of the flue liner taking several years to be sensitised it may occur in only a few minutes in the event of a chimney or flue fire.

Peacock (1983) and (1986) reports on a series of tests conducted in four factory-built steel chimneys, instrumented to study the intensity and duration of chimney fires due to the ignition and burning of combustible deposits accumulated on chimney linings over a prolonged period of time. One of the chimneys was triple-wall air-insulated while the other three were twin-wall (430 stainless steel) solid-packed (insulated) chimneys; one was exposed to cold outside air temperatures while the other two were enclosed.

During the burnout tests temperatures on the flue liners were measured on average to be 186°C below the flue gas temperature. The peak temperatures recorded on the air-insulated chimney ranged from 653°C to 906°C; on the enclosed solid-packed chimneys, 758°C to 917°C; and on the exposed solid-packed chimney a peak temperature of 1111°C was measured. Peacock also noted the visible damage to the chimneys after the series of fires. The galvanising on the outer pipe (shield) of the air-insulated chimney had dulled on the upper sections. No damage was obvious to the two enclosed solid-packed chimneys but damage was evident in all sections of the exposed chimney. Peacock (1986) says - "In the tee section, where temperatures were the highest, holes were found, over the entire surface of the inner wall. The holes ranged in size from small, barely noticeable penetrations to one approximately 50 by 80 mm." He also found buckling in both radial and longitudinal directions.

The author has been unable to locate similiar temperature measurements for uninsulated metal flue installations. In New Zealand, factory-built fully insulated chimneys are not often used (as they are in the USA and UK) but instead are usually factory-built, ventilated twin-wall installations fitted together in the field. One could expect the peak temperatures identified above to be perhaps slightly lower in air-ventilated cases due to the increased dissipation of heat.

Low Temperature Corrosion

Low temperature corrosion of metal flues has in the main been attributed to acid condensation on the upper surfaces of flue pipes. Important factors influencing acid condensation are: the sulphur content of the fuel; the excess air component of the flue gases; and the surface temperature of the flue pipe.

All fossil fuels contain some sulphur and it is the burning of these fuels (and in particular coal) with which we are concerned here. During combustion the sulphur (S) component of the fuel is oxidised to sulphur dioxide (SO_2), a portion of which is then further oxidised to sulphur trioxide (SO_3).. The conversion of 5-10% of SO_2 to SO_3 may take place in the flame and further conversion may be catalysed by solids or aerosols in the flue gases (Wright, 1984). The chemical processes are represented by:

$$S\ (s) + O_2\ (g) \rightarrow SO_2\ (g)$$

$$SO_2\ (g) + \tfrac{1}{2}O_2\ (g) \rightarrow SO_3\ (g)$$

According to Tems and Mappes (1982) a maximum of about 6% of the sulphur in the fuel can be converted to sulphur trioxide. In the presence of water vapour the sulphur trioxide forms sulphuric acid (H_2SO_4):

$$H_2O\ (g) + SO_3\ (g) \rightarrow H_2SO_4\ (g)$$

The gaseous sulphuric acid will condense on surfaces below a certain temperature (in this case on the internal wall of the metal flue). This temperature is known as the "acid dewpoint" and is commonly in the range 130°C to 150°C (Wright, 1984). The dewpoint is governed by the following equilibria and can be precisely calculated from the partial pressures of the water vapour and sulphuric acid (Halstead and Talbot, 1980):

$$H_2O\ (g) + H_2SO_4\ (g) \rightleftarrows H_2SO_4\ (aq)$$

The sulphuric acid condensate is corrosive and will readily attack metals such as mild steel:

$$H_2SO_4\ (aq) + Fe\ (s) \rightarrow FeSO_4\ (s) + H_2\ (g)$$

While stainless steels may have some resistance to corrosion by acid condensate they should not be expected to provide total protection.

Adding molybdenum can help to improve the resistance of Cr-Ni steels (e.g., AISI 316) to condensing flue gases containing sulphur compounds. Molybdenum is generally regarded as an additive which improves the pitting resistance of stainless steels (Redmond, 1982).

Solid fuel appliances should be operated at levels of heat output sufficient to keep the temperature of the flue pipe above the acid dewpoint but under certain conditions acid condensation may still occur. These could include during the warm-up and cool-down cycles of the appliance; or when appliances are fired at very low rates (left to burn overnight perhaps); and where the upper end of the flue is exposed to the outside air and is uninsulated.

Fuels

The solid fuel appliances with which this report is concerned are usually designed to burn wood and/or coal. Nonetheless people are sometimes inclined to dispose of treated timber offcuts collected from building sites and driftwood in their stoves, both of which can be detrimental to the long-term durability of a metal flue.

Furthermore, household refuse containing plastic material should not be used as fuel since the burning plastic may release hygrogen chloride which is particularly corrosive towards metals.

Coal

Coal contains very little oxygen so in order to burn effectively it requires an adequate supply of air. Coal burning appliances therefore require a grate beneath the coal to allow the air to pass through. In New Zealand there are three main coal types (Blackman, 1983); lignites, sub-bituminous and bituminous coals. Lignites and sub-bituminous coals are relatively slow-burning while bituminous coals burn faster and more fiercely, producing higher temperatures. New Zealand bituminous coalfields are mainly found in Westland.

In the previous section the hazards of acid condensation were discussed and the sulphur content of the fuel was deemed important. Gray (1985) has provided an analysis of the mean chemical composition of New Zealand coals (dry, mineral free basis). The sulphur and ash contents from his analysis have been used to derive Table 1.

TABLE 1. MEAN SULPHUR AND ASH CONTENT OF NEW ZEALAND COALFIELDS

Region	% Sulphur		% Ash		Ash:Sulphur
	range	mean	range	mean	ratio
Waikato	0.2-2.0	0.4	1.6-4.9	2.7	6.8
Taranaki	1.0-3.3	2.1	4.3-6.1	5.1	2.4
Westland	0.3-2.6	1.3	0-0	0.0	0.0
Otago	0.4-5.5	2.1	3.8-8.0	5.3	2.5
Southland	0.3-1.1	0.7	1.7-6.2	4.4	6.2

It has been reported (Milne, 1984) that if the ash to sulphur ratio is about seven or more there is much less trouble with acid deposition (as is observed in the Waikato - ratio 6.8).

Wood

Wood has a cellular structure containing pockets of air, so it does not require a grate (like coal) to burn effectively. However, it does contain moisture which reduces potential heat output since energy can be wasted in driving off moisture rather than being used to heat the room. This is why it is considered important to dry or season wood by six to twelve months storage before burning.

Softwoods (e.g., pine) tend to burn faster and hotter than hardwoods (e.g., manuka) although they contain less energy for weight. If softwoods are used, refuelling will be required more often and peak flue temperatures will most likely be higher (Blackman, 1983).

Creosote build-up in flues results when vapours, tars and soot produced from incomplete combustion of wood are deposited on the surface of the flue pipe. These deposits can dry and burn (or pyrolyse) leaving a solid residue. Cool, smouldering wood fires are the main source of creosote which if allowed to build up can ignite causing a chimney fire (Katzer and McAuliffe, 1982).

Driftwoods may be laden with salt which makes them most unsuitable as a fuel due to the corrosive effect of chloride on metal component parts of the stove and flue. These effects may be exhibited as direct attack by pitting, or in some cases, chloride stress cracking of the steel. Stress corrosion cracking requires a temperature greater than about 60°C, a corrosive environment (e.g., chloride ions), steel under stress and access to oxygen. All of these conditions will be present in stove and flue if driftwood is burned. The stresses weaken the passive oxide film allowing accelerated attack. The main stresses to be found in metal flues are those due to the curvature of the steel, residual stresses left in areas of cold work (e.g., swages and lock-folded seams) and thermal stresses due to expansion and contraction during heating cycles.

Other fuels to be wary of include timber treated with copper-chromium-arsenic (CCA) wood preservatives ("Tanalised") which may not only corrode metals but can also produce poisonous fumes and ashes.

Flue Design

Insulation of Metal Flues

Insulating metal flue pipes has often been promoted as a means to prevent acid condensate deposition and subsequent corrosion occurring - particularly in areas of the USA and UK with very cold climates. Rendle (1962) proposed a concentric aluminium shield enclosing an air space between the chimney and shield as an alternative to conventional solid thermal insulation packed between chimney and shield. Ravenscroft and Page (1966) describe how insulated chimneys can be designed to reduce acid condensation but they also point out that such conditions may still occur during the warm-up period irrespective of whether the chimney is insulated. While these sorts of chimney designs are suitable for some boilers and other low heat output appliances and perhaps in very cold climates (generally colder than experienced in New Zealand) they should not, because of the risk of over-heating, be extended for use with the pot-belly and closed combustion solid-fuel appliances to be found in many New Zealand dwellings. The only parts of a metal chimney system where these techniques can be used safely are when they are located outside the building enclosure where flue and shield are exposed to the cooler exterior air.

Stainless steel beneath insulation can be subject to pitting or chloride stress cracking, even where the insulation is nominally chloride free but exposed to minor amounts of rainwater. Chlorides from the water and/or insulation are leached in toward the warm (about 70°C) pipe and concentrate there by evaporation (Atkinson and VanDroffelaar, 1982). Attack will then proceed as described earlier.

Fry (1980) states the problem nicely - "Which is the greater risk - too much heat in the lower section, or too little heat and condensation and corrosion at the top?" Considering the failure mechanisms of the case study flues discussed later in the report, the evidence appears to suggest the former.

Lock-Formed versus Welded Seams

Katzer and McAuliffe (1982) recommend that high temperature stainless steel flue pipes be seam-locked or continuously welded, rather than of spot-welded construction. Spot-welded flues are less likely to be sensitised at the time of fabrication than continuously welded flues but they are also unlikely to be gas tight, and if the distance between spot welds is great enough there is a danger of the flue opening up between the spots when hot.

Continuously welded stainless steel seams, while gas tight, are at risk of being sensitised during fabrication ('weld decay') as discussed previously. However, this could be avoided if the weld were cooled quickly enough, as is likely with the light-gauge material currently used, according to Page (1984), or if a low-carbon type of stainless e.g., AISI 304L were used. If sensitisation is avoided during fabrication there is still the possibility, however, that the exposure time required to reach sensitisation during service could be decreased as it would be additive to the heating effects of the welding already received.

While low carbon stainless steels may offer little additional resistance to sensitisation occurring over a longer period of time (≈1000 hours) due to high temperatures (>450°C), they would provide some protection during a chimney fire or transient overfiring. According to the time-temperature sensitisation curves provided by Scott (1985) it would require at least 50 hours cumulative exposure to any elevated temperature up to 850°C before sensitisation in AISI 304L would occur.

Flues with lock-folded or welded seams are still at risk from long term high temperature exposure and from chimney fires. Furthermore, the cold-working of lock-folded seams leaves residual stresses in the steel making the seam (or other cold-worked areas such as swages or crimps) more susceptible to stress corrosion cracking caused by using sulphur or chloride containing fuels. So, provided 'weld decay' is avoided, continously welded seams are preferable to lock-folded seams as the potential problems and deficiencies of cold-working are lessened.

Alternative Chimney Design

Katzer and McAuliffe (1982) described an alternative design for a factory-built metal chimney system for use with modern closed combustion appliances. Their design introduced the concept of thermosiphon cooling of the flue. The proposed double radiation shields and inner flue are cooled by circulating air drawn in from outside the building by a thermosiphon effect created by the temperature difference between the inner and outer radiation shields. The thermal expansion properties of austenitic stainless steel are utilised to control the volume of cooling air entering the annular space between the radiation shields. When the stainless steel liner is at room temperature no cooling air is admitted, but as it heats up and expands, the space between the cowl and the radiation shield increases, allowing a larger volume of air to be drawn into the outer void replacing the warmer air escaping from the inner void or annular space.

The advantage of this type of design is that the varying rate of ventilation ensures the inner flue becomes neither too cold nor too hot - and is dependent upon the temperature of the flue. This is not to say there will never be any problems with either overheating or creosote deposit on occasions but it is, nonetheless, an improvement on many current designs.

Maintenance and Inspection

Cleaning Deposits from Flue Pipes

It is important that creosote or other deposits are not permitted to build up inside a flue pipe. Not only are they often corrosive but they can

easily build up to a level where they restrict the flow of gases in the pipe and may ignite possibly producing a fierce fire in the flue, which is not only a dangerous event in itself (surrounding timber framing may ignite from the radiation) but is also likely to reduce the life expectancy of the flue if it has not already received other obvious damage.

It is often recommended that appliances are run very hot for a short period each day with the air dampers open to flush the flue of any small deposits. For instance, Powell (1980) recommends that at least once a day and always before adding fresh fuel to the fire, the damper should be opened and the stove allowed to burn hot for 15 minutes or so. This practice will burn away small amounts of creosote at a much lower temperature than is required to remove thicker coatings that have built up over a longer period of time.

This practice, however, is not without its dangers. It may be suitable for stainless steel flues if followed exactly and if it is known that excessive temperatures are not produced on the surface of the metal flue. The danger is that the "overfired" state, albeit temporary, presents a risk of sensitising a stainless steel flue by the cumulative effect of the elevated temperatures (above 450°C for AISI type 304) resulting in earlier degradation than might otherwise be expected. Stone (1980) says that creosote may start burning at temperatures between about 430°C to 650°C. So in order to use this method to clean the flue at least 430°C would need to be reached on the creosote or flue surface (and probably a higher temperature at the appliance end to be effective higher up in the chimney). If this is to be done every day during use it is likely to reduce the life of a stainless steel flue. It is apparent that manual or mechanical methods of cleaning such a flue, while time-consuming and sometimes difficult, are still preferable - and should always be used if the thickness of the creosote layer is greater than about 1.5 mm (Stone, 1980) or 3 mm according to WHERF (1987).

Chemicals are sometimes used to clean masonry chimneys but they are usually not suitable for cleaning metal flues. The chemicals used may react with the metal flue causing rapid corrosion.

Ideally, flue pipes should be routinely cleaned by an experienced chimney sweep (a typical householder is unlikely to possess the necessary tools). Frequency will depend on the use of the appliance - at the very least once per year and as often as once per month for controlled combustion heaters if slow, smouldering fires are burned and the chimney is cold (WHERF, 1987). If the appliance is always run extremely hot there may never be any significant build-up of creosote.

Inspection of Flue Pipes

Current designs of lightweight metal flue systems do not allow for easy inspection of the inner flue liner where it is covered by a shield. Often the only practical way of conducting a thorough inspection of concealed areas is to dismantle part of the installation and remove the flue liner by lifting it up and out from the roof. This is not always a satisfactory situation and the installation of inspection ports of some description in the outer shield should be encouraged.

The surface of the steel should be closely examined for signs of rusting and degradation. If the outer surface of a stainless steel flue is dull, dark in colour and strongly tarnished it is likely to have lost the protection of its original passive chromium-oxide layer (due to inadequate corrosion resistance or sensitisation perhaps) indicating further degradation is likely in the future. Newer metal flues with a shiny but discoloured surface can give some indication of the service temperatures to which they have been exposed, provided they have not received a polymer type surface coating which will disguise the natural colours produced on heating. The discolorations (commonly called temper colours) are due to the interference effects of thin films of oxide (compare with oil films on water) formed during heating (Rollason, 1973). The thickness of an oxide film will increase or grow as the temperature increases and with the passage of time depending on the rate of growth. According to Rollason, alloys such as stainless steel form thinner films than carbon steels so that a pale straw colour on stainless steel would correspond to approximately 300°C (230°C on carbon steel). A blue colour is likely to correspond to a temperature of closer to 400°C - an indication that the service temperatures have been approaching above-optimum levels.

When a flue is heated and reaches a temperature of around 550°C, it will emit sufficient electromagnetic radiation in the visible spectrum for the first signs of a red glow to be visible. At 700°C the flue would be a dull red colour in appearance.

Smoke Testing

If the flue (and chimney in the case of inbuilt heaters) is suspected to contain cracks or perforations then a smoke test could be conducted to confirm the presence (or otherwise) of leaks. A smoke candle (low heat / high smoke producer) should be placed and lit in the appliance with a damp blanket covering the top of the flue. Some improvisation may be neccessary depending on the particular chimney and venting arrangements present. An additional person should be readily available to remove the blanket if too much smoke is leaking into the room containing the appliance. Signs to look for include smoke escaping from places other than the chimney top and also cracks in the masonry of chimneys containing insert stoves. If leaks from holes are found the appliance should not be used until the offending parts are replaced. Smoke testing in this way can be unpleasant and is not a substitute for a thorough visual inspection of the installation. It is an aid to locating cracks, gaps or other openings in and around the chimney and/or flue.

Code Requirements

Restrictions placed on materials permitted to be used for metal flue pipes, contained in New Zealand and some overseas standards, are outlined in this section.

New Zealand Standard NZS 7421:1985 Specification for the Installation of Solid Fuel Burning Domestic Appliances (NZS 7421) Clause 309.1.

0.6 mm (minimum) stainless steel is permitted. Type 304 and 316 are stated to be proven materials, but any type of stainless steel may be used if selected in accordance with the maximum temperature permitted by Note (8) of Table 1 of NZS 7401:1985, Specification for Solid Fuel Burning Domestic Appliances.

1.2 mm (minimum) steel or 0.8 mm (minimum) steel with vitreous enamel on the inner surface, or any other material which the appliance manufacturer can show has suitable properties, are also permitted.

Australian Standard AS 2918-1987 Domestic Solid Fuel Burning Appliances - Installation (AS 2918) Clause 2.3.

0.55 mm (minimum) stainless steel is permitted (Type 301, 302, 304, 310, 316 or 321 austenitic stainless steel or Type 430 ferritic stainless steel. For corrugated flexible flue pipe within a chimney only, the nominal thickness is to be not less than 0.13 mm).

0.8 mm (minimum) low carbon enamelling steel with a vitreous enamel coating over both inner and outer surfaces.

United States - National Fire Protection Association Standard NFPA 211-1984 Standard for Chimneys, Fireplaces, Vents and Solid Fuel Burning Appliances: (NFPA 211).

Chimney connectors are required to be of listed factory-built chimney material or of steel pipe having resistance to corrosion and heat equivalent to 0.48 mm galvanised pipe (for up to 152 mm diameter) or 0.58 mm (for between 152 and 254 mm diameter). A connector (sometimes known as a stove-pipe) is used to connect appliances to the vertical chimney unless the chimney is attached directly to the appliance.

In general, chimneys used with solid fuel burning appliances must be of a factory-built and listed chimney or chimney unit type. The WHERF Study Manual (1987) reports that from April 1987, most wood heaters with a factory built chimney will be required by NFPA 211 to use a chimney that meets the more severe "Type HT" requirements of UL 103 but a listed factory-built fireplace must still meet the requirements of UL 127.

United States - Underwriters Laboratory Standard UL 127-1981 Factory-Built Fireplaces (UL 127) Clause 5.4 and Table 5.2.

0.30 mm Series 300 and Types 430 and 446 stainless steel or 0.66 mm porcelain-coated steel-base metal are permitted for flue-gas conduit material with inside diameter 305 mm or less.

United States - Underwriters Laboratory Standard UL 1482-1981 Room Heaters, Solid Fuel Type (UL 1482) Clause 6.6.

0.81 mm (minimum) series 300 or 400 stainless steel and carbon steel sheets coated with type A19 ceramic (for parts not readily visible after installation).

Canadian Standard CSA B365-M1980 Installation Code for Solid-Fuel Burning Appliances and Equipment (B365) Clause 5.3.4.

0.33 mm (minimum) for a steel flue pipe diameter up to 150 mm and 0.41 mm for flue pipe diameter up to 200 mm. A flue pipe under this standard is interpreted to be that which connects an appliance to the chimney and is similar to the chimney connector or stovepipe in US terminology.

British Standard BS 4543: Part 2: 1976 Factory-Made Insulated Chimneys Part 2. Specification For Chimneys For Solid Fuel Fired Appliances (BS 4543) Clause 4.1.1.

0.4 mm (minimum) stainless steel sheets complying with the requirements of 316S12 or 316S16 of BS 1449: Part 2: 1975 (for the metal flue liner only).

British Standard BS 6461: Part 1: 1984 Installation of Chimneys and Flues for Domestic Appliances Burning Solid Fuel (including wood and peat) Part 1: Code of Practice for Masonry Chimneys and Flue Pipes (BS 6461) Clause 6.1.

1 mm (minimum) stainless steel (Types 316S11, 316S13, 316S31 or 316S33).

3 mm (minimum) low carbon steel.

1.2 mm (minimum) low carbon steel with vitreous enamel coating.

Note that grades 316S11 and 316S13 are low carbon forms of AISI type 316 while 316S31 and 316S33 are similiar to AISI type 316. These British specifications are according to BS 1449: Part 2: 1983.

Summary

A comparison of these overseas standards shows that there are differing requirements between countries. Stainless steel is permitted by all, with the minimum required thickness ranging from 0.3 mm to 1.0 mm. Some standards allow most common types of stainless to be used while others are very specific and permit only particular types. The New Zealand requirements appear to be similar in degree to the Australian, stricter than the Canadian and more lenient than the British, who require a low carbon form of 0.4 mm (26g) thick AISI 316 (i.e., AISI 316L) for factory-built insulated flues and at least 1.0 mm thick (20g) AISI 316 for flues installed in masonry chimneys.

CASE STUDIES OF FAILED FLUES

In July 1987, a contract was negotiated by BRANZ with DSIR (Industrial Processing Division) to investigate the failure of four stainless steel flues supplied by BRANZ. The results of the investigation were reported by McIlhone (1987) and provided an opportunity to relate the actual performance of some degraded flues with many of the potential problems and hazards identified in the literature. The results of the investigation are summarised in this section.

Flue A

This flue was made from 0.6 mm thick AISI type 304 stainless steel and was 102 mm in diameter. It was of a continuous lock-folded spiral seam construction and had been used with a solid fuel chip heater burning mainly wood. The owner had observed the flue to be glowing red on occasions indicating a flue surface temperature in excess of 550°C. The flue was shielded with an annular air space of 50 mm from ceiling level through to just above roof level. Ventilation was by means of heated air from the room passing into the annular space between flue and shield at ceiling level which was then vented directly up to the outside. After six to seven years of use the top of the assembly was found to be tilting and the flue was removed and replaced. On removal, extensive corrosion leading to perforation of the lock-folded seam was found in the shielded area below the level of the flue skirt. This area of the flue was examined by a DSIR metallurgist and is shown in Figure 5.

Tarnished and untarnished areas of the flue were examined and the tarnished area was found to have had an unacceptable microstructure (possibly sensitised) believed to have been formed during service at temperatures in excess of 450°C. The flue failed by intergranular corrosion, embrittlement and cracking originating from both the inside and outside surfaces as a result of the unacceptable microstructure. An example of this type of corrosion failure found in Flue A is shown in Figure 6. Some chloride stress corrosion cracking from the outside surface was also discovered to be present. The intergranular embrittlement was thought most likely to be due to carbide precipitation from the matrix with diffusion of carbon from the carburising atmosphere the next most likely mechanism.

Flue B

This flue was made from 0.6 mm thick AISI type 430 stainless steel and was 150 mm in diameter. It had a lock-folded longitudinal seam construction with a swaged roll at the end of each section and was used with a pot-belly stove. After about three years use it was noticed that the swaged roll on the bottom section of the flue next to the appliance outlet had tarnished, corroded and perforated. The remainder of the flue section was straw-brown coloured and appeared to be in relatively good condition. This corroded area was examined by a DSIR metallurgist and is shown in Figure 7.

The microstructure adjacent to the failed area was examined using a boiling sulphuric acid and copper sulphate etch test and found to be acceptable. A micrograph showing such an acceptable structure in Flue B (magnified 600 times) is shown in Figure 8. The main reason thought to be responsible for the failure was general corrosion from the inside surface suggesting that AISI type 430 may have too low a general corrosion resistance to be suitable for the purpose for which it was used. However, it is not known whether in this case the flue gases were higher in chloride and sulphur species than usual. In addition, some thinning and work-hardening of the steel at the swaged roll could have been expected due to the cold roll processing, causing perforation to occur earlier than in other areas of the flue.

Flue C

This flue was made from 0.6 mm thick AISI type 304 stainless steel and was 120 mm in diameter. It had a lock-folded longitudinal seam construction with no swaged rolls. Very little is known about the history or background of the flue, nor its installation and use. The bottom section adjacent to the appliance was generally a straw-brown colour in appearance with a number of blue-tarnished and blotchy areas. The exact age of the flue is unknown but the lock-folded seam was observed to have corroded and come apart. The failed seam was examined by a DSIR metallurgist and is shown in Figure 9.

The microstructure adjacent to the failed seam was examined and found to be acceptable using ASTM standard practices. The flue was noted to have failed by transgranular cracking, the most likely cause of which was thought to be chloride induced stress corrosion cracking from the inside surface under the effect of residual and service stresses, and the presence of chloride ions and possibly sulphur in the flue gases. Figure 10 shows a cross-sectional view through the seam of Flue C and reveals the cracking originating from the inside surface. While the fact cannot be confirmed, it is thought that this flue was used to burn driftwood.

Flue D

This flue was made from 0.6 mm thick AISI type 304 stainless steel and was 150 mm in diameter. It was of a continuous lock-folded spiral seam construction and had been used with a coal-burning appliance. The flue had been insulated with vermiculite from 200 mm below ceiling level through to above roof level and below the cowl. The vermiculite had been placed in the annular space between the flue and an outer galvanised steel shield. After a fire was observed in the flue with flames emerging from the top of the assembly, the five-year-old flue was removed and inspected. In the insulated section of the flue enclosed within the ceiling space, severe corrosion and cracking leading to perforation was apparent. Some cracking on the exterior surface of a lock-folded seam in the uninsulated section below ceiling level was also observed. The entire flue was darkly tarnished and, at least on the surface, bore little resemblence to stainless steel. A DSIR metallurgist examined both areas. Part of the flue is shown in Figure 11.

The microstructure of the flue was found to be unacceptable and, similarly to Flue A, was believed to have been formed at temperatures in excess of 450°C and most likely to be due to sensitisation of the steel. A micrograph illustrating the unacceptable structure is shown in Figure 12. The mode of failure was mainly intergranular corrosion and embrittlement with one area of cracked seam failing by chloride induced stress corrosion cracking as described for Flue C. It is also likely that the manner in which this flue was insulated contributed to the premature failure. The surface temperatures reached on the inner flue would have been higher than if the annular space had been ventilated to the outside. The increase in the flue surface temperature may have been enough to sensitise the steel much more readily and in a much shorter timespan than it may have otherwise done, leading to its decreased corrosion resistance.

Conclusions from Case Study Investigation

One of the conclusions reached by McIlhone (1987) on the above four flue failures is restated here:

> "Based purely on the results of this investigation, AISI 304 appears to be a suitable material for this application provided that the service temperature does not exceed 450°C, and that fuels with low levels of chloride and possibly sulphur are used. AISI 430 may have too low a corrosion resistance to be a suitable alloy."

Regarding this statement, it is known that it is very difficult to ensure that service temperatures on the flue do not exceed 450°C. Solid fuel appliances are not easily controlled to the degree that gas, oil or electrical appliances are - some of which may have safety thermostats to cut out the heater if excessive temperatures are reached. Therefore, if the use of AISI type 304 stainless steel as a flue material is to be continued, it must be accepted that it is likely to have a limited service life and probably less than that of the appliance. The exact life expectancy will be largely dependent upon the way in which the associated appliance has been used, the type of fuel used and the level of maintenance undertaken.

Of the three austenitic (AISI 304) flues examined, in no case could primary failure be ascribed to a general corrosion mechanism resulting in the gradual wearing away of the flue wall. They all exhibited failure by cracking type mechanisms. Because of this only a small benefit would result from specifying the next heavier gauge (e.g., 22g) of steel. Of greater benefit would be the specification of a more sensitisation-resistant and stress corrosion resistant type of stainless steel.

CONCLUSIONS

1. In general, common types of ferritic, martensitic, duplex and precipitation-hardening stainless steels are not suited for use as solid fuel stove flues. Austenitic stainless steels are the preferred choice for this purpose.

2. AISI type 304 stainless steel is likely to be adequately durable provided it is not exposed to temperatures in excess of 450°C. Since flue temperatures are difficult to control, AISI type 304 is likely to have a limited life expectancy as a flue - and probably less than that of the appliance with which it is used. This will necessitate regular inspection and maintenance of the flue during its life. If it is deemed desirable that a flue pipe material should have an unlimited life span then a more durable material than AISI 304 will need to be used.

3. AISI type 316 is likely to be more durable than AISI 304 and should give adequate performance if not exposed to temperatures above 500°C. However, like AISI 304, the corrosion resistance of this material will suffer if it is subjected to chimney fires or severe overfiring.

4. Low carbon types (AISI 304L, 316L) of stainless steel will provide better protection than AISI 304 or AISI 316 against sensitisation due to chimney fires or transient overfiring but are still prone to long term sensitisation by exposure to elevated (>450°C to 500°C) temperatures.

5. Of the common types of stainless steel considered here, AISI type 316L is likely to be the most durable as a flue pipe material at a non-prohibitive cost. It has slightly better resistance to long-term sensitisation than AISI 304 or 304L, it offers some protection against sensitisation due to chimney fires and transient overfiring (which AISI 304 does not but 304L does) and also has better corrosion resistance to condensing flue gases than AISI 304 or 304L.

6. Other more highly alloyed heat-resistant austenitic stainless steels, for example, 310S (25% Cr, 20% Ni, 0.08% C) while much more expensive, are likely to be very durable and are unlikely to be sensitised during use.

7. The use of an inherently more resistant type of stainless steel will be of greater benefit than using the next heavier gauge (e.g., 22g). This is because failure of stainless steel flues has been observed to be primarily by cracking rather than by general corrosion.

8. Flues used with an appliance burning coal (particularly bituminous coal containing sulphur) are generally subjected to a more severe (potentially hotter and more corrosive) environment than those used with slow combustion wood stoves.

9. Driftwood, CCA treated (or "Tanalised") timber or plastic material from household refuse should not be burned in a solid fuel appliance with metal chimney components.

10. Solid-fill insulating material such as vermiculite can cause overheating of the inner flue in some installations and for this reason should not be used within the building enclosure. If used in a shielded arrangement outside the building, care should be taken to avoid settlement of insulation resulting in an uninsulated gap in the annular space at the very top of the chimney. Waterproofing the flue shield to exclude the entry of rain water or salt spray is also important.

11. Cold-working of stainless steel flues should be minimised as such areas will be more susceptible to corrosion as a consequence of additional residual stresses in the steel and possible micro-structural changes due to work-hardening. Longitudinal lock-folded seams are preferable to spiral wound lock-folded seams as the total length of seam, and hence the total amount of cold-working, is less. Care should also be taken not to cold-work areas of the steel more than is absolutely necessary. Stress relieving annealing of cold work will not usually be a practical or economic alternative.

12. If welding techniques are used to form flue seams, manufacturers should examine their processes to ensure that the microstructure of the stainless steel (particularly AISI 304) is not sensitised at the time of fabrication. If necessary, representative samples of their product could be tested to ASTM A262 (for austenitic stainless steel only).

13. Manufacturers should seriously consider designing a means of inner flue pipe inspection into their overall flue kit design, particularly if use of AISI 304 continues.

14. Cleaning a stainless steel flue by opening the damper and allowing the stove to burn hot for a period of time each day is likely to reduce the life expectancy of the flue. Mechanical methods used by an experienced person are preferable if the useful life of the flue is to reach its potential. If the thickness of the creosote layer is greater than 2-3 mm, mechanical methods should always be used.

15. Frequency of flue cleaning will depend on the rate of deposit build-up but should be no less frequent than once per year and perhaps even as often as once per month during the heating season if creosote accumulation is excessive.

16. Careful inspection of the flue should accompany any regular maintenance. The surface of the steel should be examined for signs of rusting and perforation. If cracks or perforations are suspected a smoke test of the installation could be undertaken.

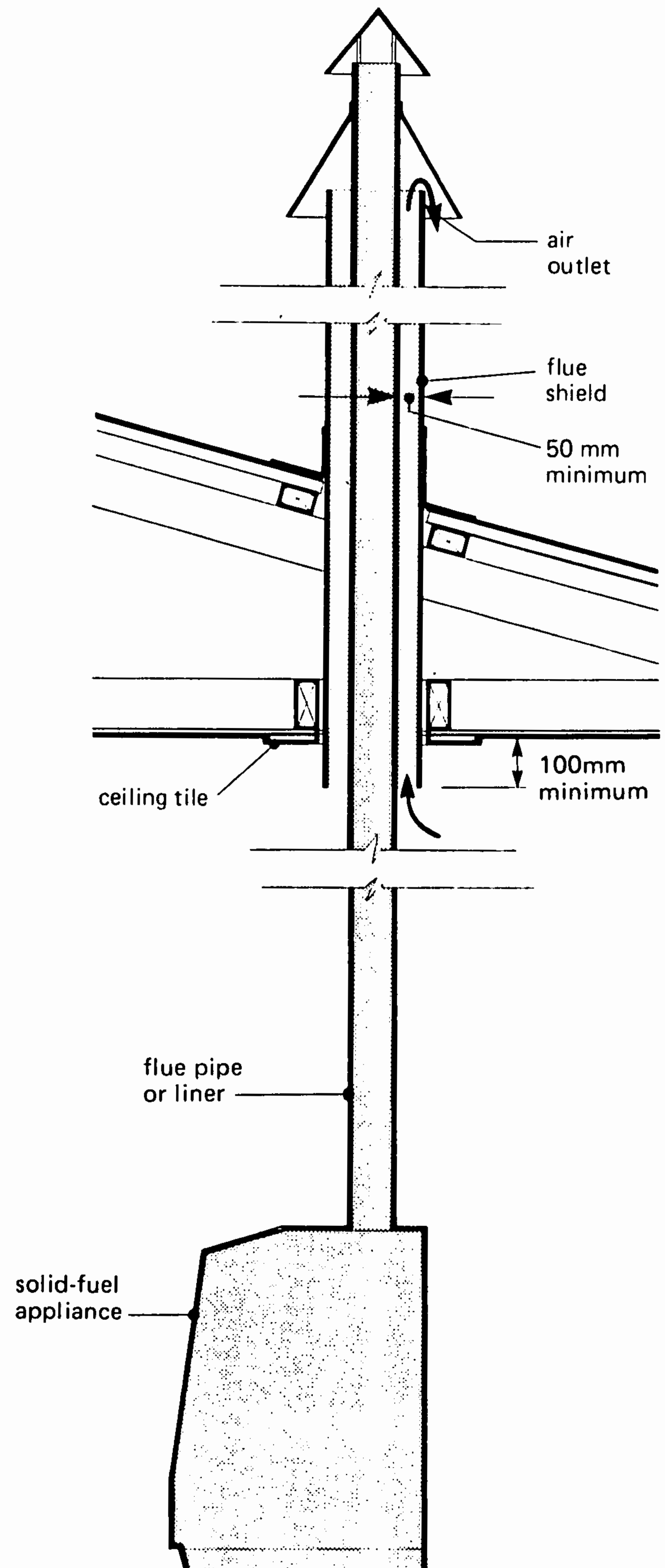

Figure 1 : Schematic of a free-standing solid-fuel stove installation.

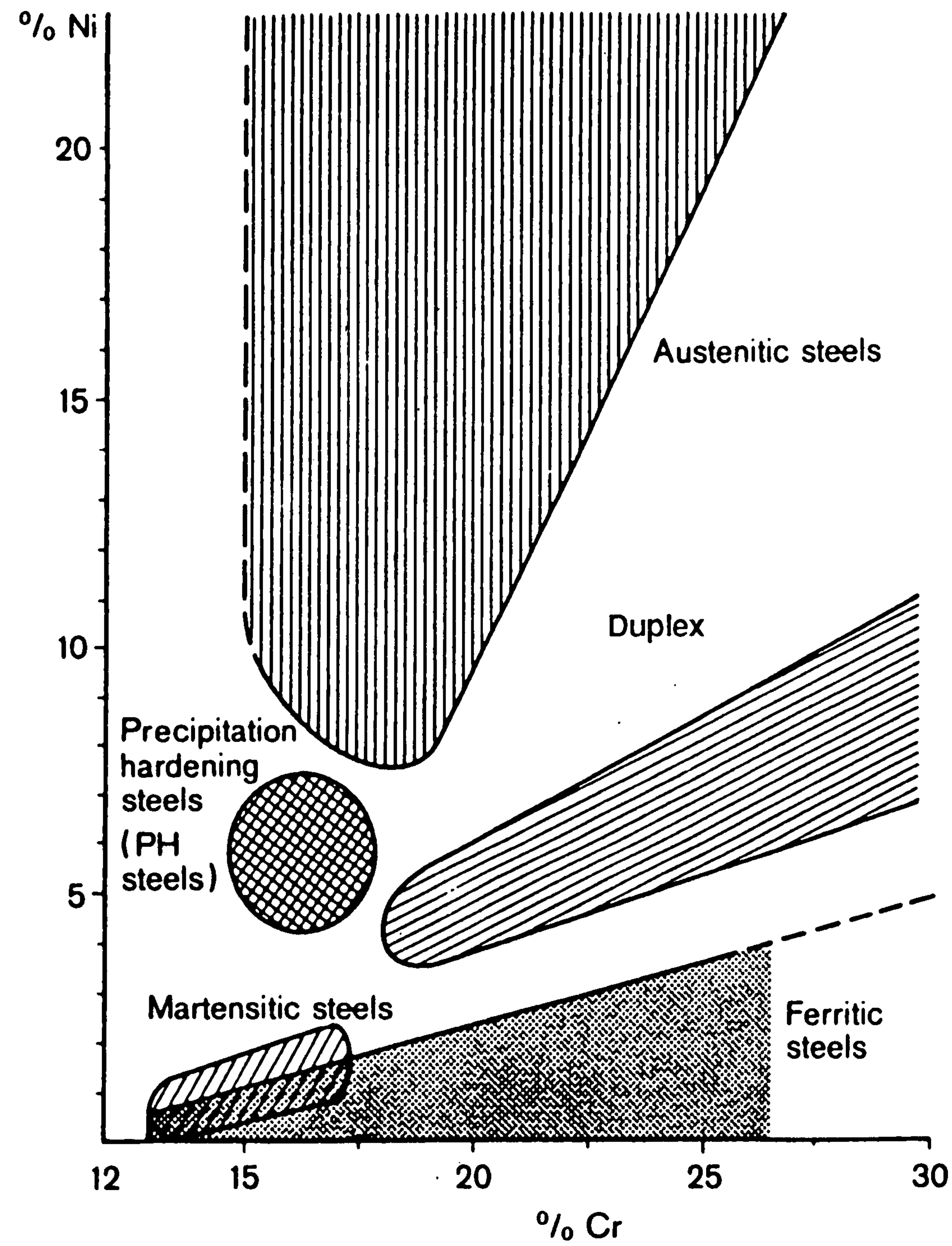

Figure 2 : **Relationship between chromium and nickel contents for the five basic types of stainless steel (from Miller and Boulton, 1982).**

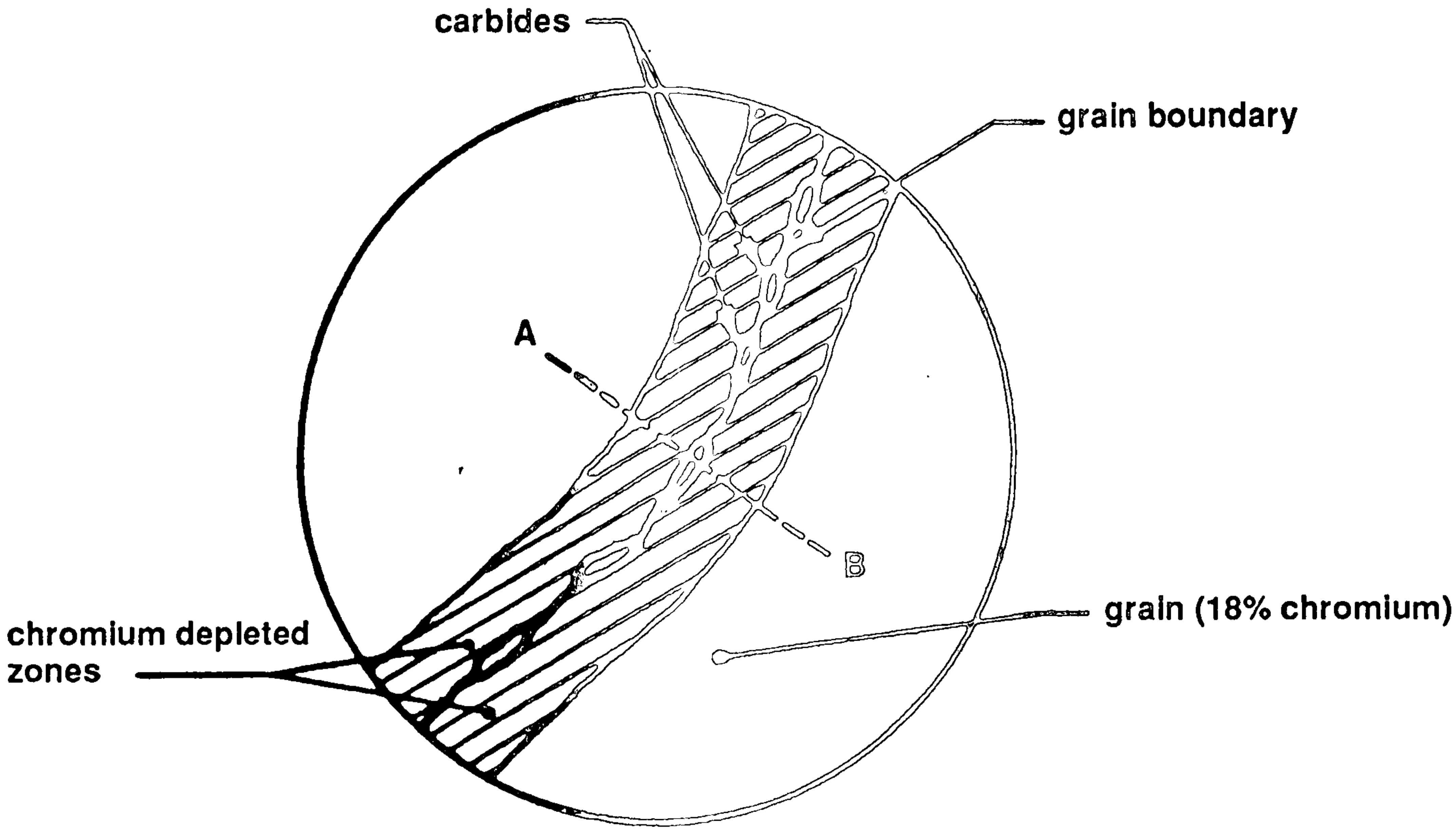

Figure 3a: Schematic representation of a grain boundary in a sensitised austenitic stainless steel (from Lyth, 1975).

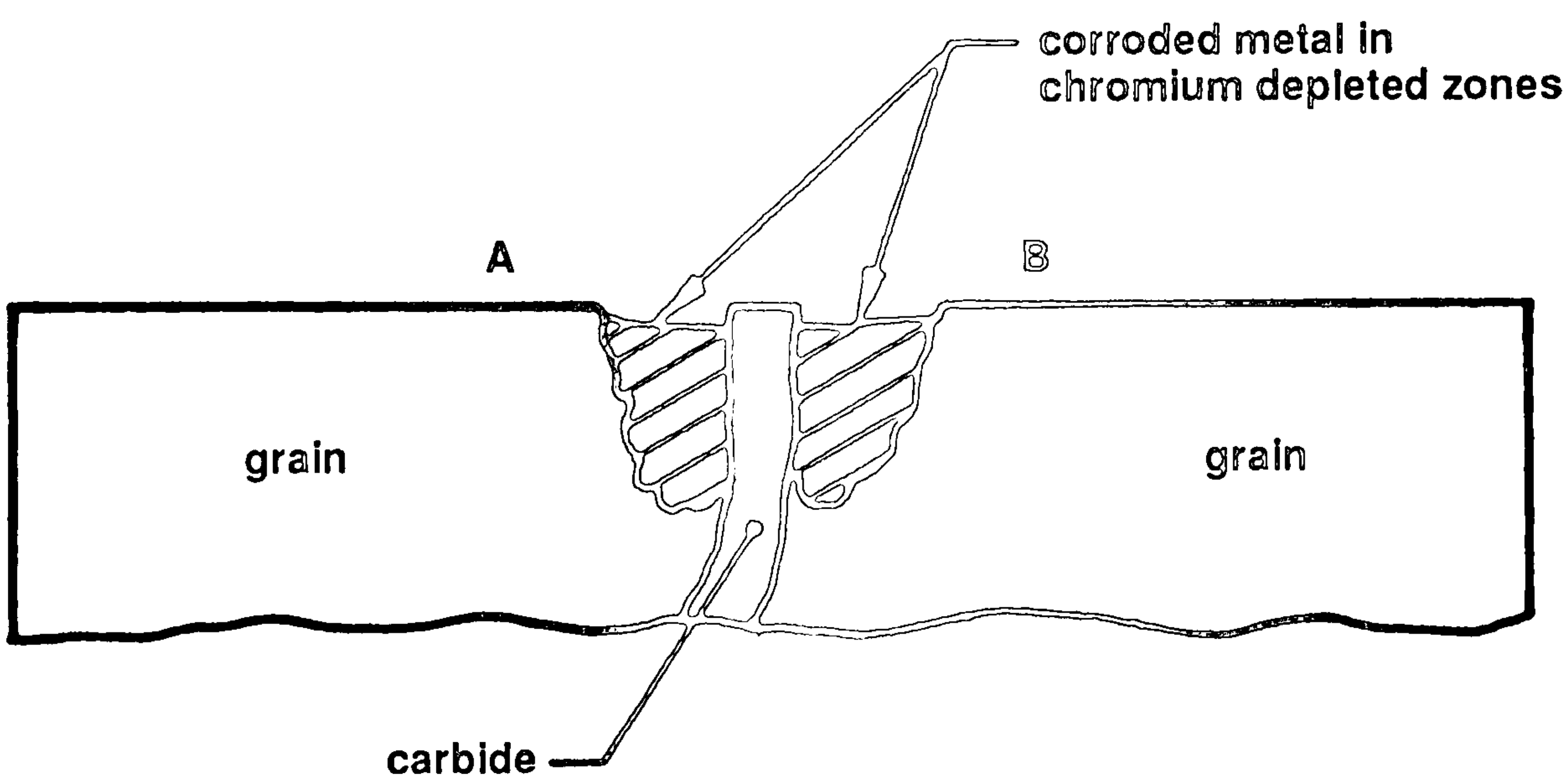

Figure 3b: Section A-B through chromium depleted zones adjacent to grain boundary (from Lyth, 1975).

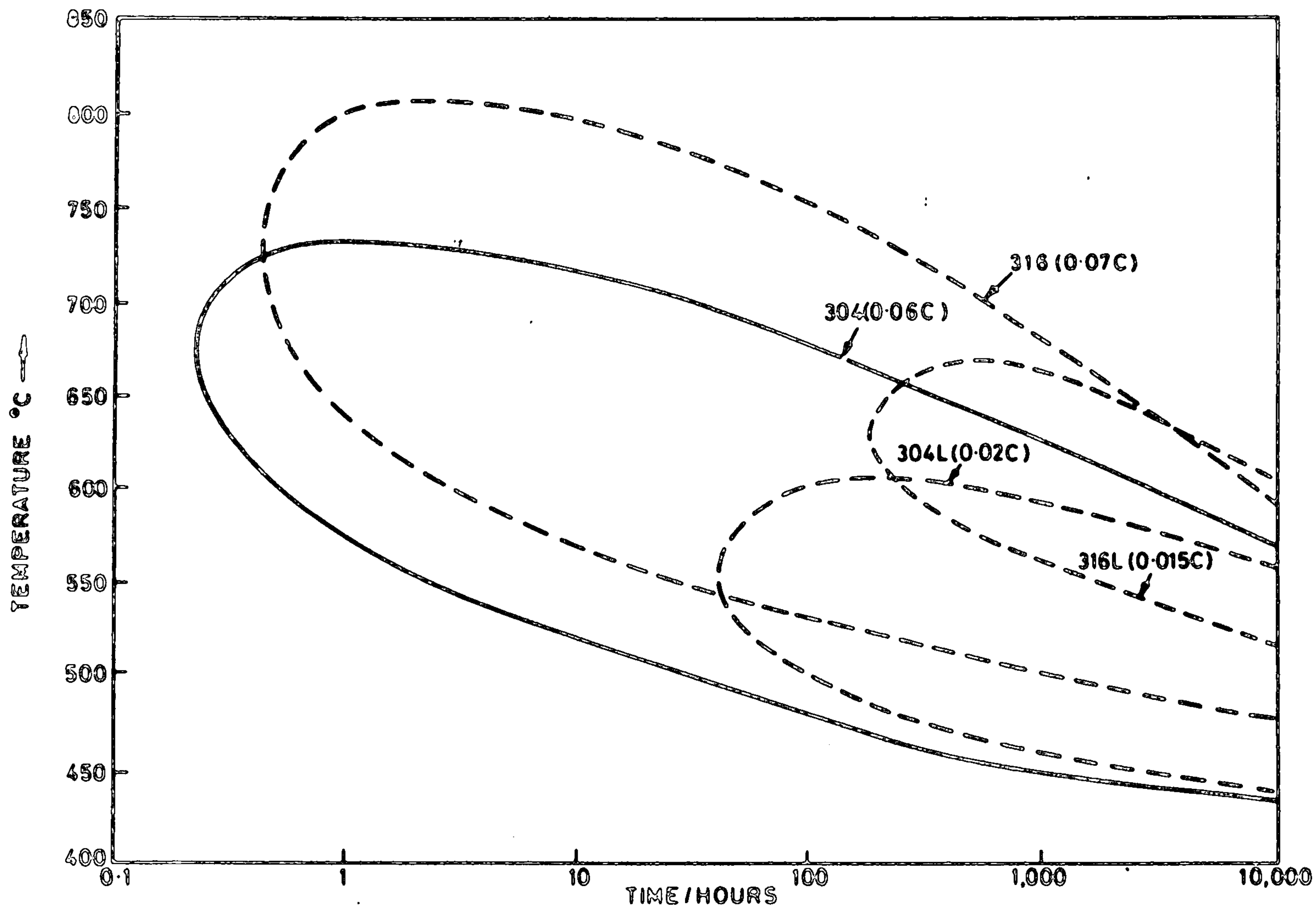

Figure 4: **Time-Temperature Sensitisation Curves (from Scott, 1985).**

Figure 5: Flue A - AISI type 304 .

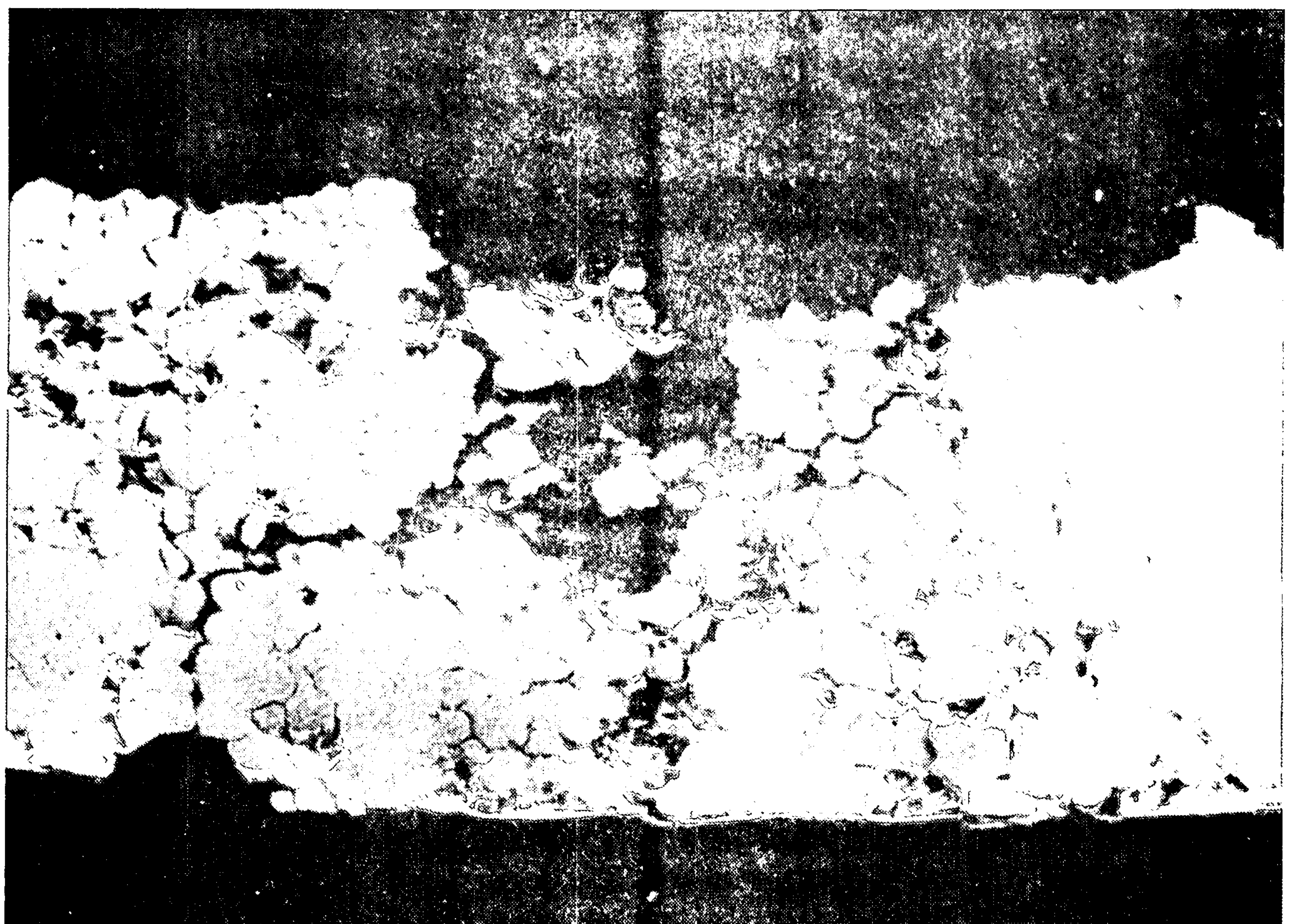

Figure 6: Cross section through Flue A showing intergranular corrosion, embrittlement and through-cracking (from McIlhone, 1987) .

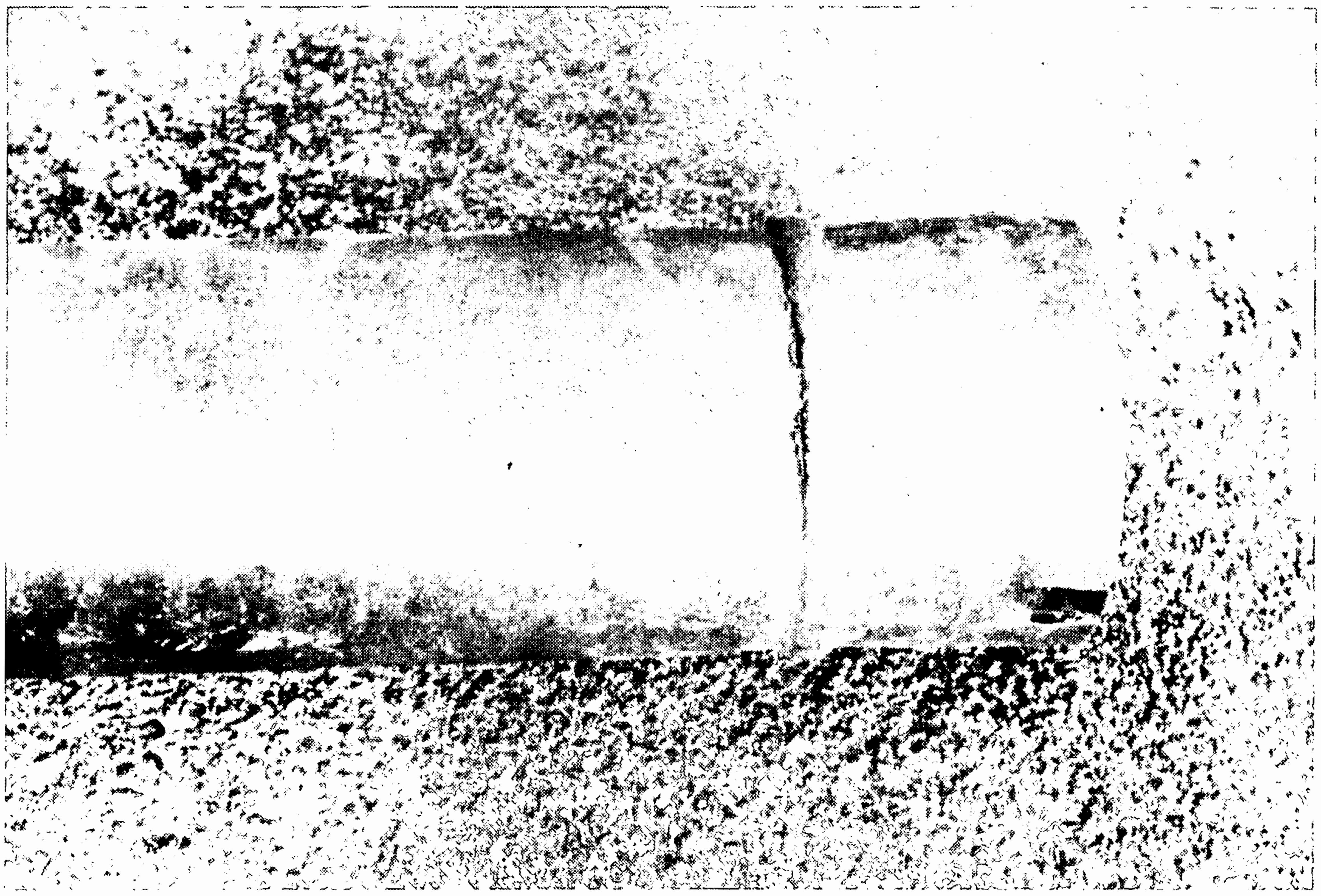

Figure 7: Flue B - AISI type 430 .

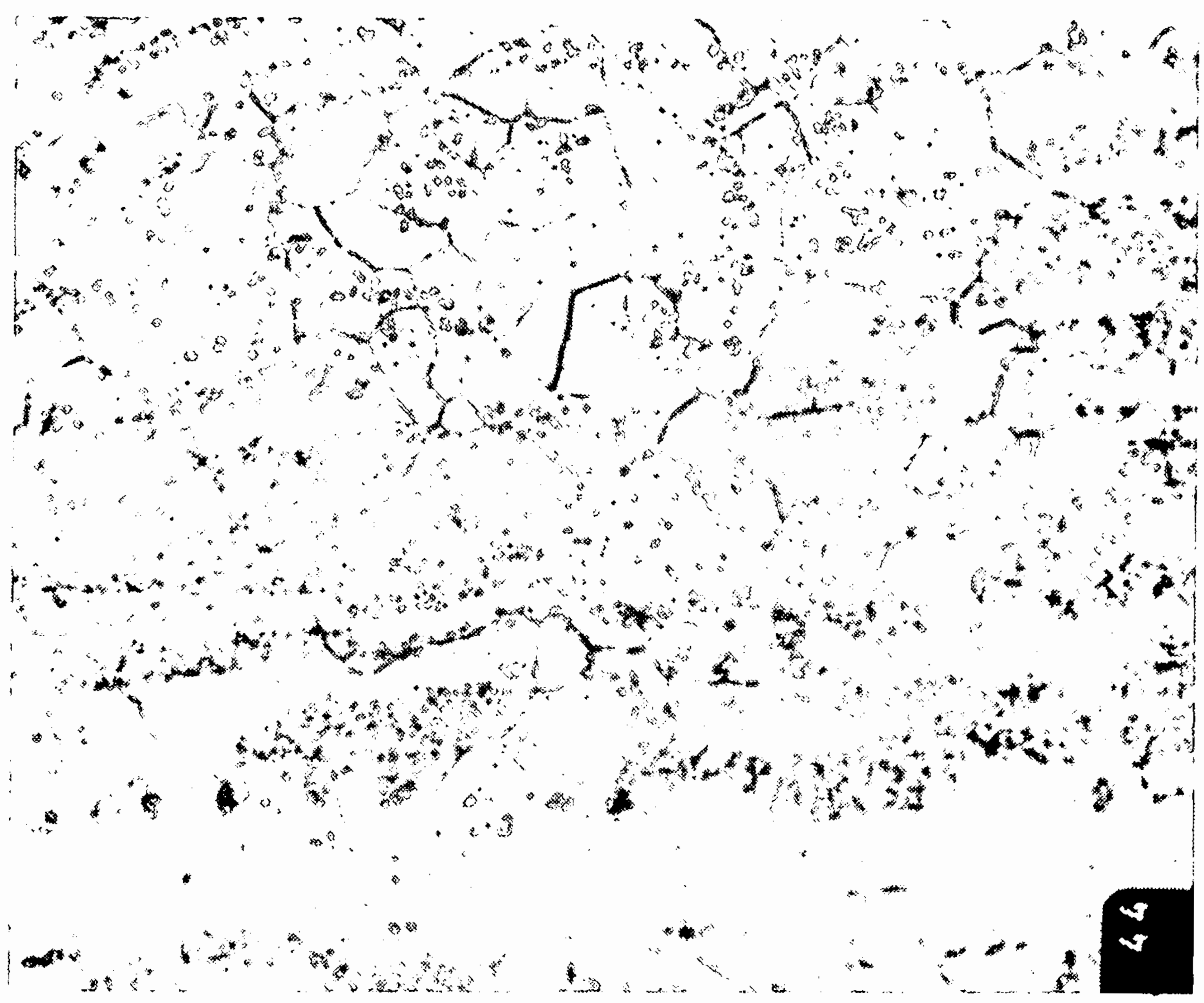

Figure 8: Acceptable dual structure for sample of Flue B by the Boiling Sulphuric Acid / Copper Sulphate Etch Test (from McIlhone, 1987).

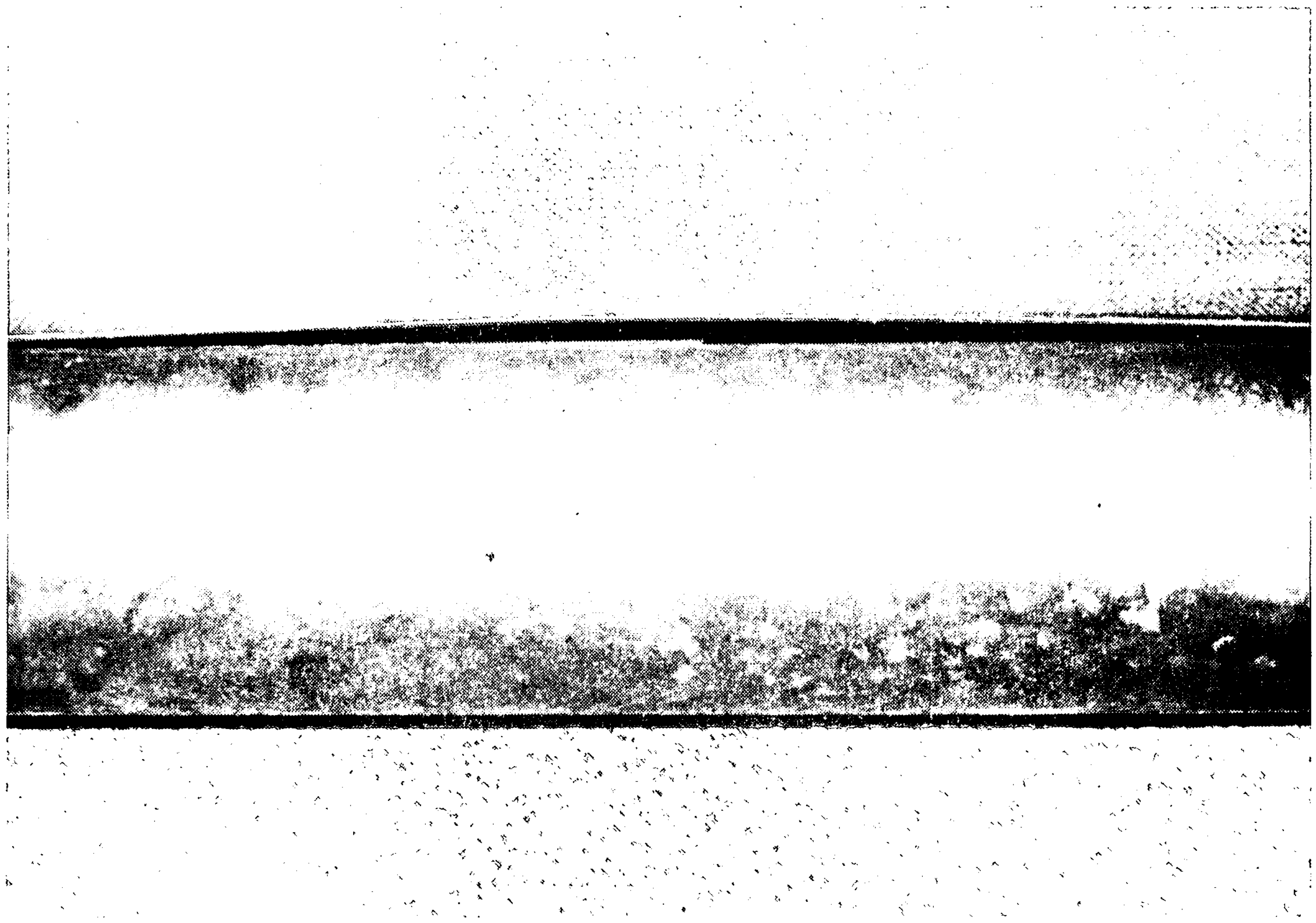

Figure 9: Flue C - AISI type 304 .

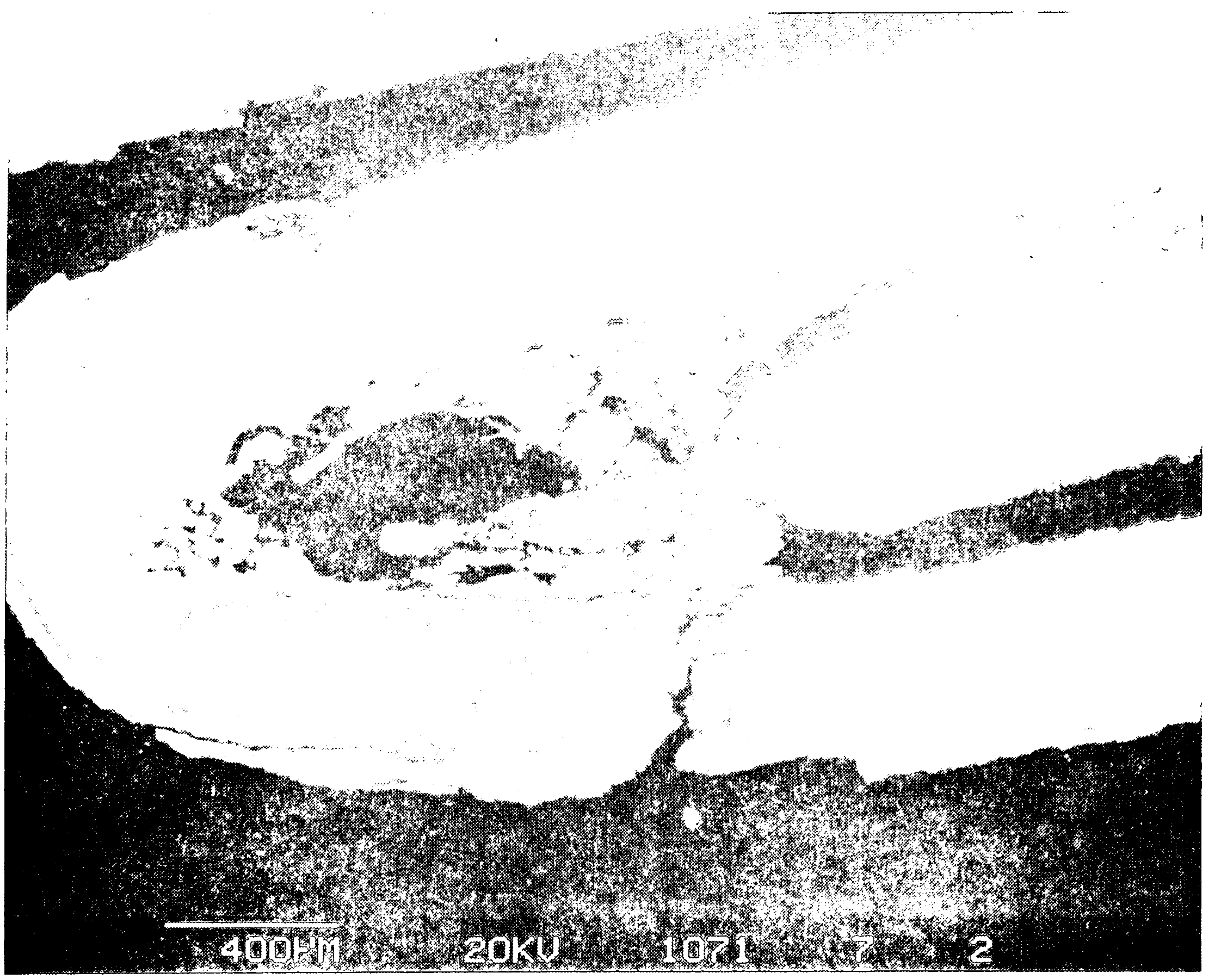

Figure 10: Cross section through the seam of Flue C showing crack propagating from the inside wall (from McIlhone, 1987) .

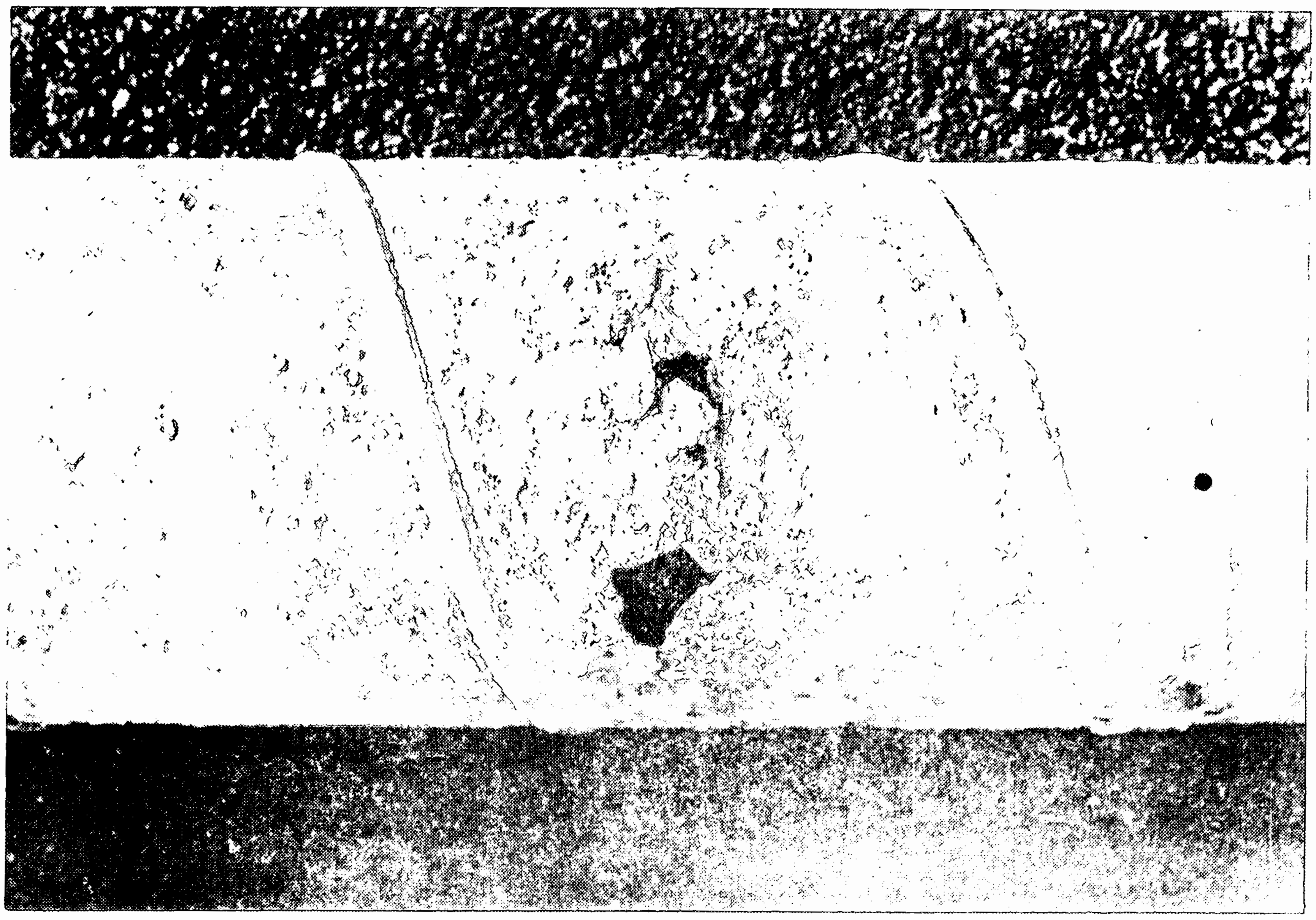

Figure 11: Flue D - AISI type 304 .

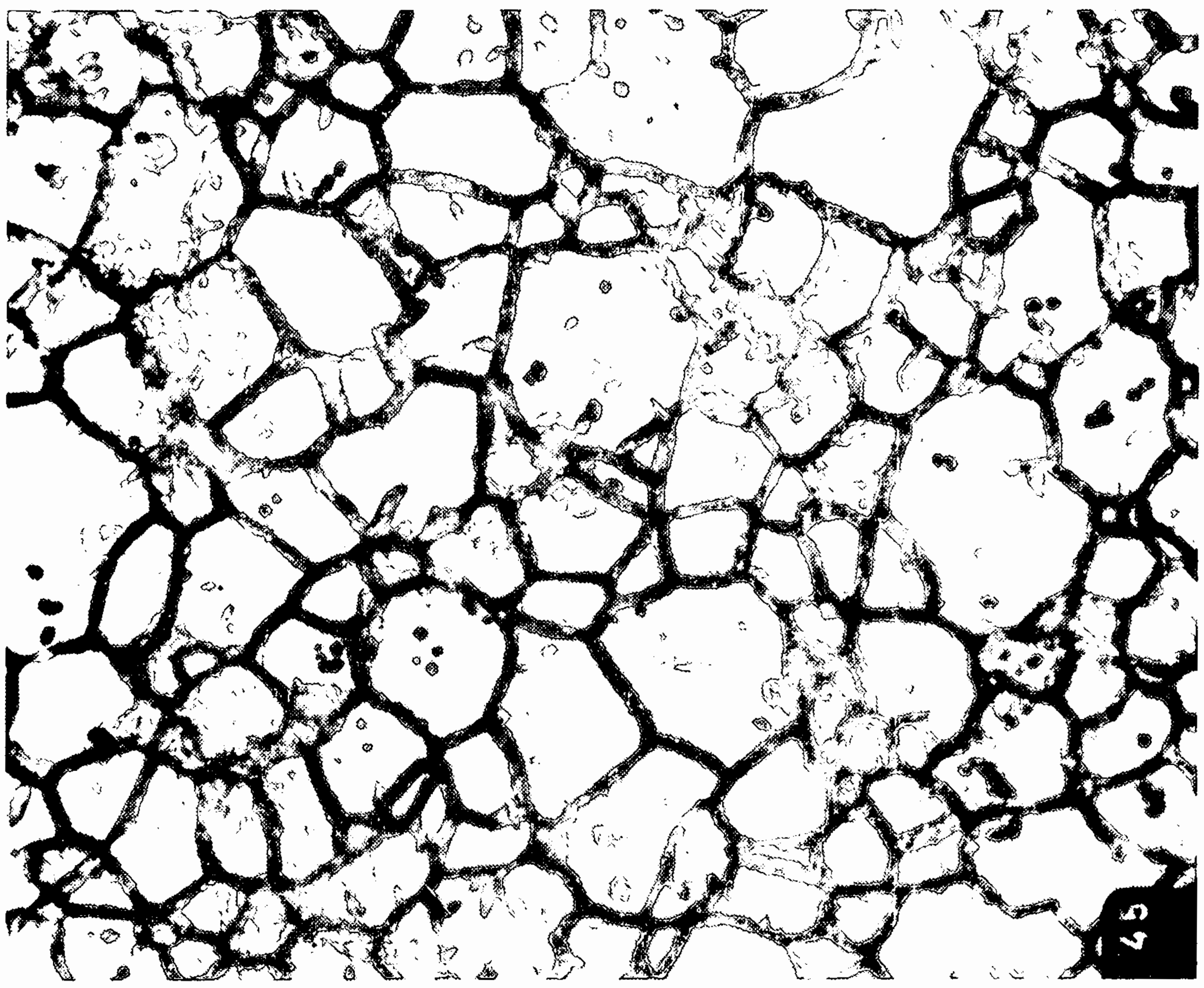

Figure 12: Unacceptable ditch structure for sample of Flue D in ASTM A262 Practice A Test (from McIlhone, 1987) .

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