NBS TECHNICAL NOTE 833

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Fire Department Ground Ladders— Results of a Preliminary Study

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Fire Department Ground Ladders—Results of a Preliminary Study

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Mr. William E. Clark, former Director, Department of Fire Protection, Prince George's County, Maryland, who first called our attention to some of the problems fire departments are having with ladders.

CONTENTS

ILLUSTRATIONS

FIRE DEPARTMENT GROUND LADDERS - RESULTS OF A PRELIMINARY STUDY

Harvey P. Utech[1]

The key performance requirements for fire department ground ladders were determined. Existing ladder standards were reviewed and found to be unnecessarily restrictive in some areas and inadequate and unrealistic in others. Included in the report are metallurgical studies of three ladders that failed in service as well as a correlation of hardness with tensile and yield strength for 6061-T6 alloy.

Key words: Aluminum; fire department; ladders; performance requirements; standards.

1. INTRODUCTION

The National Bureau of Standards has conducted a preliminary study in which the key performance requirements for fire department ground ladders have been identified. The purpose of this report is to describe the results of that study.

Fire departments most frequently use ladders for the following purposes:

1. To deliver fire men and their equipment across vertical and horizontal distances in order to:

   a. Accomplish firefighting operations (figure 1)
   b. Rescue trapped occupants (figure 2)
   c. Permit building ventilation (figure 3), and
   d. Provide alternate means of escape, should interior stairways be unexpectedly blocked (figure 4).

2. To provide a platform from which firemen can:

   a. Direct hose streams (figure 5), and
   b. Perform mechanical work on the supporting structure (figure 6).

In addition, fire department ladders are occasionally used for horizontal bridging and as battering rams.

To accomplish these purposes, fire departments have at their disposal two types of ladders:

1. Aerial ladders, which are power-driven, up to about 100 feet in length, and mounted on a specially designed chassis usually referred to as a ladder truck (figure 7). Recently, there has been a trend toward replacing aerial ladders with a bucket at the end of an articulated or telescoping boom. Aerial ladders are generally used where a long reach is necessary, as to the upper floors of a high-rise.

2. Ground ladders, which are hand-carried and raised manually. They are used for the lower levels of a building. Figure 8 shows a variety of aerial and ground ladders in use.

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[1]Presently working as a consulting engineer in Washington, D.C.

Only ground ladders will be discussed in the remainder of this report; however, many of the performance requirements for ground ladders apply qualitatively to aerial ladders and articulated booms as well.

Several types of ground ladders are considered in this report; they are defined as follows:

1. Wall, straight, or single ladders - ladders consisting of one section; these typically range from 12 to 24 feet in length.

2. Extension ladders - ladders with two or more sections; these range in length from 24 to 55 feet extended.

3. Roof ladders - straight ladders equipped with folding hooks at one end and designed to lie flat on the roof surface; these range from 12 to 20 feet in length (figure 9).

Other types of ground ladders, such as combination, folding, and pompier are infrequently used by fire departments and will not be specifically discussed in this study. The reader interested in a more detailed review of fire department ladder practice as well as an exposition of standard fire department carries and raises is referred to reference [1].[2]

Virtually all ground ladders used in this country are made from either of two materials:

1. Wood - the traditional material. Still favored by some departments (e.g. Los Angeles F.D.) primarily for its low electrical conductivity. Disadvantages of wood ladders are their relatively high weight and susceptibility to deterioration with age.

2. Aluminum - much more widely used than wood. Preferred for its light weight and low maintenance but its high electrical conductivity is a drawback.

There are two existing voluntary standards that appear to apply to fire department ground ladders:

1. NFPA No. 193-1972 - Standard on Fire Department Ladders - Ground and Aerial [2].

2. American National Standard A14.2-1972 - Standard for Portable Metal Ladders [3].

The first of these standards is published by the National Fire Protection Association and specifically applies to fire department ground ladders. The second standard appears to apply to fire department ground ladders as well, since it states that it "is intended to prescribe rules and minimum requirements for the construction, care, and use of the common types of portable metal ladders, in order to insure safety under normal conditions of usage" (par 1.2). The standard goes on to say that so-called special-purpose ladders are not covered by the standard but it is difficult to judge from the American National Standards Institute (ANSI) definition of Special-Purpose ladders (section 3) whether fire department ladders are in this category or not. At any rate, as this report shows, the requirements of the ANSI standard are considerably more stringent than those of the NFPA standard and, for that reason, the requirements of both have been included in this study. While ANSI A14.2 cites performance criteria for light, medium, and heavy duty ladders, only the requirements for heavy duty properly apply to fire department ground ladders and therefore, only those criteria will be cited in this report.

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[2]Figures in brackets indicate the literature references at the end of this paper.

Figure 1. Using aerial ladders to direct hose streams to best advantage. (photo courtesy Chet Born, San Francisco Fire Department)

Figure 2. Accomplishing a rescue down a ladder. (photo courtesy Chet Born, San Francisco Fire Department)

Figure 3. Ladders are often needed to provide access for ventilation.

Figure 4. Ladders sometimes provide the firefighter's only means of escape.

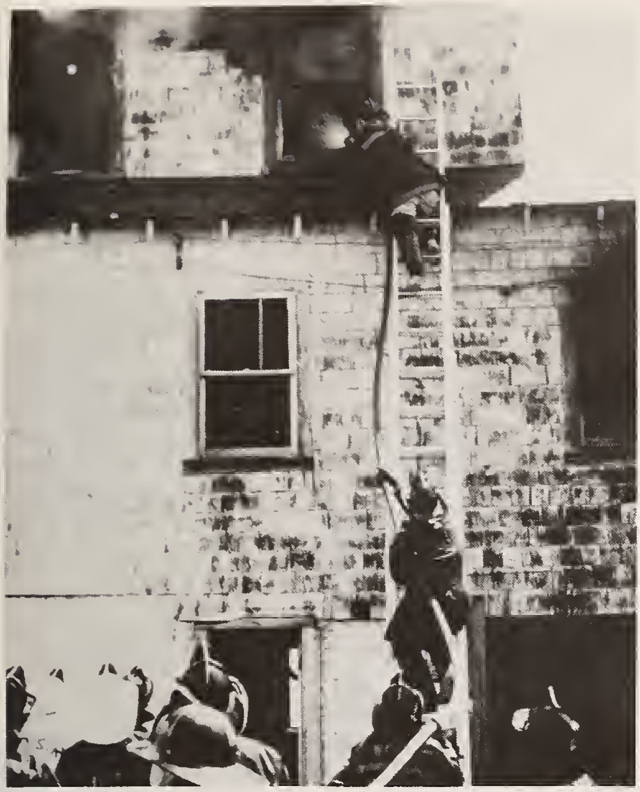

Figure 5. Using a ground ladder to bring the nozzle closer to the seat of the fire. Note the leg-locks of both men and the upper man's leaning to the left. (photo courtesy of Joseph M. McDonagh, Fire Service Extension Dept., University of Maryland)

Figure 6. A ladder provides a platform from which to accomplish over-hauling. (photo courtesy of Joseph M. McDonagh, Fire Service Extension Dept., University of Maryland)

Figure 7. Ladder trucks not only provide a mount for the aerial ladder but are used for stowing most ground ladders as well.

Figure 8. A typical scene during a serious fire.

Figure 9. Roof ladders are designed to lie flat on the roof, held in place by large, top-mounted hooks.

Several recurrent themes will be illustrated at various points in this report:

1. The firefighter, on a regular basis, makes more severe demands upon his ladders than virtually any other ladder user. This stems largely from the following unique characteristics of the fireman's job:

   a. Emergency conditions, where time is of the essence,
   b. Poor lighting, caused by darkness or smoke,
   c. An uncontrolled working environment.

Because of these conditions, firemen cannot always observe the same precautions (e.g. proper angle of set, firm footing) expected of other users.

2. The metal fire department ground ladders examined in this study have <u>not</u> been designed to withstand the service conditions of firefighting.

3. Some existing fire department ground ladders are demonstrably unsafe under the severe conditions to which they may be exposed.

4. The existing voluntary consensus standard for fire department ladders is inadequate.

The remaining sections of this report are devoted to a description of what the author regards as reasonable performance requirements for fire department ground ladders. Each section is organized in similar fashion. First, the need for the performance requirement is explained. Next, the test methods and requirements of existing standards are discussed. Then, the performance of existing ladder designs is reviewed. Each section concludes with a brief set of recommendations.

2. DIMENSIONS

Ladders are generally classified by fire departments in terms of length. A typical assortment of ladder sizes likely to be found on a ladder truck is shown in table 1. The width of a ladder determines its lateral stability as well as the ease with which two men can pass on the ladder. Of considerable importance too is stacking profile which determines whether a ladder will fit into the available space on a ladder truck.

Table 1. Assortment of Ground Ladder Sizes Typically Found on Ladder Trucks

Number	Size	Number of Sections
1	50 foot or 40 foot	2 or 3
1	40 foot	2
2	35 foot	2
1	28 foot	1
1	20 foot	1
1	16 foot	1
1	14 foot	1
1	10 foot	1

2.1. Existing Standards

NFPA 193 has no definition for length and no requirement for width or stacking profile. It simply states "Ladder widths across the outside of the ladder beams shall be as specified by the purchaser to insure proper ladder nesting. The usable length shall be indicated on the ladder in a suitable manner." (par 109) However, NFPA No. 19 standard on fire apparatus [4] does carry a definition of ladder length: "Lengths shall be measured when extended and shall not be the simple sum of the lengths of the sections" (par 9310). This definition leaves unresolved the question of whether a fire department ladder measuring 23' 6" is rated as 23-foot ladder or a 24-foot ladder. The same NFPA 19 is less helpful on the subject of ladder widths; it says simply, "Widths shall be consistent with lengths . . ." (par 9310)

American National Standard A14.2 is considerably more explicit on both length and width. It states that "the size of a single ladder is designated by the overall length at the side rail, excluding any foot or end caps, with a tolerance of ±1/2 inch" (par 5.2.3) . . . . "The size of an extension ladder is designated by the sum of the lengths of one side rail of each section measured along the side rails, excluding any foot or end caps. A tolerance of ±1/2 inch shall be allowed per section."

The American National Standard also specifies that for single ladders, "The minimum clear width between side rails shall be not less than 12 inches for ladders 10 feet and under and shall increase 1/8" for each additional foot of length" (par 5.2.1), while for extension ladders (par 5.2.2), "The minimum clear width between side rails at the bottom of the base section shall not be less than ----

Ladder Size	Minimum Clear Width Between Side Rails
Over 16', up to and including 28'	14"
Over 28', up to and including 40'	15"
Over 40', up to and including 72'	18"

2.2. Existing Ladder Performance

The designated lengths of four manufacturers' ladders are compared with actual extended lengths and lengths defined in accordance with ANSI A14.2 and NFPA 19 in table 2. The ladders supplied by manufacturers B and C did not meet the length requirement of NFPA 19. One of the three ladders of manufacturer A also fails the requirement. On the other hand, manufacturer D's wooden ladder exceeded the NFPA length requirement by 2 feet.

Table 2. Ground Ladder Sizes

Manufacturer	Designated Length (ft)	No. of Sections	Sum of Section Lengths[a]	Actual Extended Length[b]	Actual Rail Width at Base[a]
A	24	2	27' 8 3/4"	23' 6"	15 7/8"
A	30	2		30' 10"	
A	35	2		35' 6"	
B	20	2		19' 10"	
C	24	2	23' 2"	19' 11"	21 1/2"
C	32	2		30' 3"	
C	35	2	39' 2"	34' 9"	21 1/4"
D	35	2		37' 0"	

[a]in accordance with definition of American National Standard A14.2 [3].
[b]in accordance with requirement of NFPA Standard 19 [4].

Three of the five ladders that failed the NFPA requirement were checked against the ANSI "sum of section length" requirement. Two exceeded the ANSI requirement by three and four feet (thus meriting a longer size designation, were the ANSI definition being used); the third fell 10 inches short of even that definition.

Based on the data in table 2, it is possible that a fire department ordering a 24-foot, 2-section ladder could wind up with one as short as 19' 11" or as long as 23' 6" extended.

The three ladders checked in table 2 for width easily met the requirements of ANSI A14.2. However, it is interesting to note the 35 percent difference in width between the 24-foot, 2-section ladders of manufacturers A and C.

2.3. Recommendations

The ANSI definition of ladder size overstates usable length and is therefore judged inappropriate for fire department ground ladders. The definition in NFPA 19 is basically a good one but it should utilize more explicit language such as the following:

> "The size of a single ladder is designated in feet by the overall length at the side rail, excluding any foot or end caps. The size of an extension ladder is designated in feet by overall length at the side rail, excluding any foot or end caps, when the ladder is fully extended. Fractions of a foot shall be disregarded. Example: A ladder measuring 24' 10" shall be designated as a 24-foot size."

This definition should be incorporated in NFPA 193 and fire departments should make this length requirement mandatory in their purchase specifications.

A study should be performed to determine appropriate width requirements for ground ladders. Factors to be considered should include lateral stability, ability of two men to pass on the ladder, and space available for ladders on apparatus. Pending results of that study, the minimum width requirements of ANSI A14.2 should be adopted for fire department ladders.

The space available for ladder storage on fire trucks should also be standardized, so that any existing manufacturer's ladder of given size and number of sections will fit in the storage space allotted for that size ladder.

3. LOAD-CARRYING CAPACITY

The most important characteristic of a ladder is its ability to carry a load. When a ladder is positioned normally and loaded at one point with a weight as shown in figure 10, the load L can be resolved, for purposes of analysis, into two mutually perpendicular forces: F_p, a force perpendicular to the plane of the ladder and F_A, an axial force parallel to the axis of the ladder. The relative magnitudes of these forces are dependent upon the angle θ at which the ladder is set. As θ decreases, F_p becomes larger and F_A smaller until, when the ladder is horizontal, F_p, is equal to the load L and F_A is zero. Conversely, as θ increases, F_A becomes larger and F_p smaller until, when the ladder is vertical, F_A is equal to L and F_p is zero. Thus, simple geometry makes it possible to calculate F_A and F_p from a knowledge of L and θ.

$$F_p = L \cos \theta \qquad (1)$$

$$F_A = L \sin \theta \qquad (2)$$

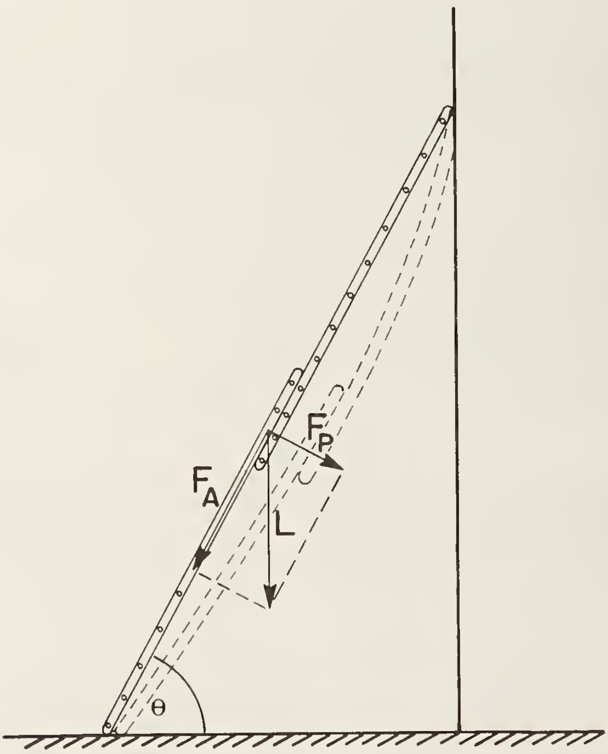

Figure 10. Sketch illustrating the simple loading of a ladder.

Figure 11. When a ladder is supported unevenly at the top and then loaded, it twists as illustrated here.

There are limits to the amount of deformation any structure can withstand before it buckles and fails. Were the loading of a ground ladder as simple in practice as the sketch in figure 10 suggests, it would be a fairly simple matter to devise a test method to evaluate the load-carrying capacity of a ladder. Unfortunately, the situation represented by the simple sketch in figure 10 represents an idealized picture. The applied load is assumed in the figure to be static, vertically downward, and evenly distributed between both side rails. In actual practice, the loading of ladders will be far more complex. To begin with, loads will generally be applied at several points along a ladder rather than concentrated at one point as shown in figure 10. The ladder may be resting on uneven ground so that one side rail is bearing more load than the other. The support at the top of the ladder may also be uneven, resulting in the twist illustrated in figure 11. Rather than static, loading will usually be dynamic as firemen move up and down the ladder. The kind of work a fireman does on a ladder results in additional complex loadings. For example, a fireman frequently has to push, pull, or reach from a ladder as illustrated by the photograph in figure 6. He may often have to manipulate a hose from a perch on the ladder (figure 5), forcing the ladder to absorb the reaction force of the hose. These result in additional stresses which complicate the loading conditions far beyond the idealized conditions of the sketch in figure 10.

3.1. Existing Standards

NFPA 193 gives the load-carrying capacity of various types of ladders as follows (par 132):

"ROOF LADDERS - when resting on roof, these ladders are satisfactory with a man on every other rung.

WALL LADDERS

a. For solid beam type up to 20-foot length, not over two men on ladder.
b. For solid beam type over 20 feet, not over three men on ladder.
c. For trussed type up to 20 feet, not over three men on ladder.
d. For trussed type over 20 feet, not over four men on ladder.

EXTENSION LADDERS

a. For solid beam extension ladders from 16 to 26 feet, not over two men on ladder.
b. For solid beam ladders over 26 feet, not over three men on ladder.
c. For trussed ladders not over 26 feet, not over three men on ladder.
d. For trussed ladders 26 to 36 feet, not over four men on ladder.
e. For trussed ladders 36 to 45 feet, not over five men on ladder.
f. For trussed ladders over 45 feet, not over six men on ladder."

The above load limit recommendations are based on the ladder supported at the top end against a building with the butt of the ladder at a distance not to exceed one-third the ladder length away from the building (approximately 55 degree angle), and preferably with the butt of the ladder placed one-fourth of the ladder length away from the building (approximately 65 degree angle). These angles are measured from the horizontal with the ladder in position. At angles less than these the load limit on the ladder will decrease accordingly."

This specification of load-carrying capacity contains several weaknesses:

1. Defining load-carrying capacity in terms of number of men lacks precision since the weight of firemen could range from less than 200 to over 300 pounds (the latter case for a heavy-set fireman, fully equipped, and carrying a load of hose). No indication is given of the average weight assumed in setting the criteria in the standard.

2. The multiplicity of criteria for wall and extension ladders (length, type, and rail construction) would be difficult to recall on the fireground.

3. The angles stated in the specification are incorrect. The angles 55 and 65 degrees should be 70.7 and 75.5 degrees, respectively.

4. No guidance is given as to how much the maximum permissible load changes with angle of ladder set.

ANSI A14.2 is briefer and more specific (section 3): "A heavy duty (Type I) ladder shall be capable of supporting a 250 lb. load . . . These ratings are based on a safety factor of four [4]. For non-self-supporting ladders, the values are based on using the ladder at an angle of 75 1/2° from the horizontal." Here is a firm commitment to support a given load when the ladder is used at a stated angle. In contrast to the NFPA specification, there is no dependence on such factors as length, type, and rail construction.

Both the ANSI and the NFPA standards use a horizontal bending test to evaluate a ladder's load-carrying capacity. However, details of the test method differ significantly between the two standards. In both procedures, the ladder is supported in a horizontal position with vertical supports located 6 inches from either end. In both procedures, a load is applied at the center of the ladder and the permanent set at the center after removal of the load may not exceed certain limits. In the NFPA test (par 135), sections of extension ladders are tested individually, a 200 lb load is applied, and the permanent set criterion is 1/8 inch. In the ANSI test (par 6.1.1), extension ladders are tested as a fully extended unit, a 250 lb load is applied, and the permanent set criterion is 1/1000 of the effective span of the side rails.

The ANSI test is more stringent. The applied load is higher; the permanent set criterion is much lower; and, most important of all, extension ladders must be tested as a fully extended unit. The significance of the latter point is shown schematically in figure 12. The failure of a ladder is dependent on the stress in the outer web of the rail section. That web stress is dependent upon the bending moment applied to the ladder. The bending moment reaches a maximum at the center of a simply supported horizontal ladder such as that shown in figure 12a and is the product of one-half the applied load, L, and the distance from the ladder support to the load, Y. Thus,

$$M_{max} = \frac{L}{2} \cdot Y \tag{3}$$

When sections of a two-section extension ladder are tested individually, the distance from the support point to the applied load is only slightly more than half of what it is when the same load is applied at the center of the fully extended ladder. The bending moment, and hence the maximum stress in the outer web of the rail section, is similarly reduced by approximately one-half. For three-section ladders, the figure is 1/3; for four-section ladders, 1/4, etc. This is illustrated graphically in figures 12b and 12c.

Thus, when a ladder passes the ANSI horizontal bending test (250 lbs. applied in the center of the fully extended ladder), the user can be justifiably assured that the same ladder can support the load capacity promised for a heavy duty ladder, i.e. 250 lbs when the ladder is placed at an angle of 75 1/2° (although not necessarily with the promised safety factor of four, as

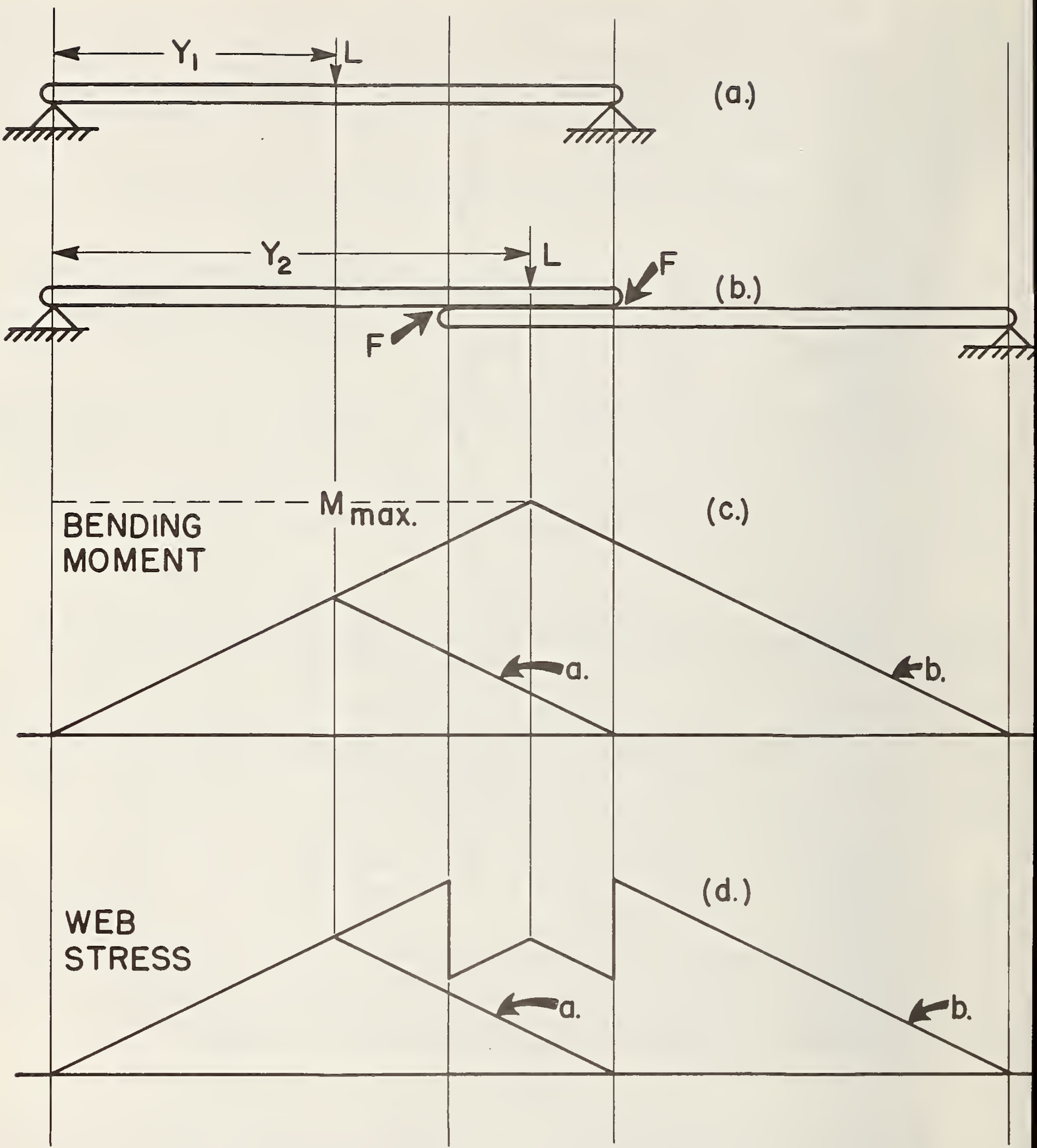

Figure 12. Illustrating the difference between the NFPA test for load-carrying capacity (a) and the ANSI test (b). The latter produces the higher maximum bending moment as shown in (c). However, the maximum stress in each ladder section occurs at either end of the overlap section as shown in (d).

discussed below). However, the fireman whose ladder has passed the NFPA horizontal bending test has no such assurance. All he knows, for the reasons discussed in the preceding paragraph, is that his fully extended 2-section ladder, placed at a 75 1/2° angle will support a little over 100 pounds. The NFPA table for load-carrying capacity states that two, three, and even four men can safely climb a two-section ladder. Assuming 200 pounds per man, that is eight times the load for which the ladder has been tested. The comparison is worse for a three or four-section ladder. The NFPA 193 test procedure for load-carrying capacity is therefore inadequate.

Both ANSI A14.2 and NFPA 193 state that the horizontal bending test provides a safety factor of 4 when the ladder is used at the recommended angle of 75 1/2°. However, this is not true if the following conditions are taken into account:

1. The axial load (F_A in figure 10) also contributes to the deflection of the ladder.

2. Dynamic loading occurs as firemen climb, descend, and move about on ladders. It is a generally accepted rule of thumb that a dynamically applied load increases the effective load by a factor of two.

3. In practice, other loads will be applied to ladders at the same time as the simple axial and perpendicular loads shown in figure 10. For example, the application of a twisting load about one of the side rails during ladder use could significantly reduce its load-carrying capacity.

There is one additional requirement related to load-carrying capacity in NFPA 193: "Structural members of ladders shall be constructed of aluminum alloy having a minimum ultimate tensile strength of 35,000 pounds per square inch. (Present aluminum alloys 6061-T6 and 6062-T6 satisfy the above requirements.)" (par 101) Such a requirement, while perhaps of some value as a quality control criterion, does not adequately define the load-carrying capacity of the ladder, since that depends not only on the tensile strength of the material but also on its cross-sectional area and on the ladder design.

3.2. Existing Ladder Performance

The preceding discussion indicates that NFPA 193 does not provide an adequate test of the load-carrying capacity of fire department ground ladders. The National Bureau of Standards has investigated two recent accidents involving ladders, both of which resulted in serious injury to the men on them. In both cases, the ladders appeared to have passed all of the test requirements in NFPA 193 but failed in normal use with two men on them. Subsequent metallurgical investigation of both failures at the National Bureau of Standards revealed probable defects, which were judged sufficient in both cases to cause the ladders to fail, but not sufficient to be detected by the methods of NFPA 193. These two service failures are described in detail in Appendices A and B.

Three representative ground ladders have been tested to failure in horizontal bending at the National Bureau of Standards. The results are shown in table 3. Each ladder reported in the table is a 2-section ladder of the truss type. The tests were conducted by applying loads in 50-pound increments at the center of each fully extended ladder. After application of each load increment, the entire load was removed and the ladder checked for evidence of permanent set. The load was increased beyond the onset of permanent set until the ladder failed completely. Both the load to produce permanent set and the load at failure are reported in table 3.

Table 3. Horizontal Bending Tests to Failure Performed on Two-Section Extension Ladders

Manufacturer	Nominal Length (ft)	Permanent Set[a] Load (lbs)	Permanent Set[a] Moment (ft-lbs)	Failure Load (lbs)	Failure Moment (ft-lbs)
A	30	750	5,500	1,200	8,900
C	24	400	1,900	470	2,200
C	35	350	3,000	365	3,100

[a]ANSI criterion: span length/1000.

The results show that all three ladders qualify under the ANSI criterion for a "heavy duty (Type I)" ladder in that they are all capable of supporting a 250-pound load. However, note that the ladder of manufacturer A does this with a considerably wider margin of safety. Since the ladders are of different lengths, their relative strengths can be more realistically compared by comparing maximum bending moments (eq (3) above). These are also listed in table 3. Such comparison shows that the ladder of manufacturer A is of a substantially stronger design than either of those of manufacturer C.

All of the ladders tested failed at the point where the overlapped portion of the ladder ends, i.e. points F in figure 12b. (Both of the service failures reported in Appendices A and B also failed at these points.) It is not difficult to account for this observation.

As mentioned above, the failure of a ladder is dependent upon the stress in the outer web of the rail section. That stress depends upon the bending moment, as discussed above, and also upon the cross-sectional area of the ladder. That area will be larger within that portion of the ladder where butt and fly sections overlap and thus, the stress in that portion of the ladder will be proportionately reduced. The result is shown qualitatively in figure 12d. The stress is greatest at the ends of the overlap portion of the ladder.

3.3. Recommendations

Tests for load-carrying capacity are needed that more realistically simulate the loads imposed during service than does the simple horizontal bending test. What is needed is a detailed study of how ladders are loaded in actual practice. The results of such a study must then be translated into a set of new tests that can be used to assess more realistically the ability of a ladder to stand up under complex loading conditions.

However, as an interim measure, the requirements of ANSI A14.2 for the load-carrying capacity of heavy-duty ladders should be incorporated into NFPA 193.

4. HIGH TEMPERATURE STRENGTH

It is inevitable that ladders used in firefighting become exposed to heat. This can happen in any number of ways. One is illustrated in figure 9 where a roof ladder has been placed directly on a hot roof and appears about to be subjected to direct flame contact. Another type of exposure is illustrated by figure 13; here, hot gases and radiant heat from the fire itself and from hot building parts serve to heat the ladder. The most severe type of exposure occurs when the ladder is subjected to flames emanating from a burning window of a flashed-over room. The temperatures of such flames are shown in the sketch in figure 14. Such occurrences are by no means infrequent. One large Eastern

Figure 13. Fire department ladders are frequently subjected to radiant and convective heating.

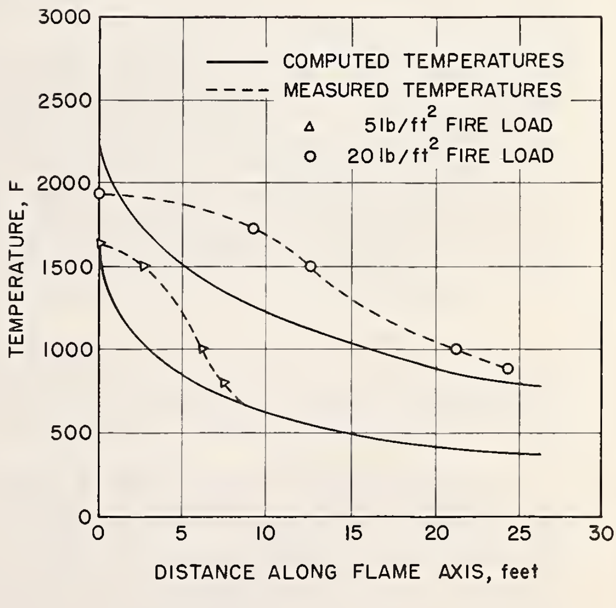

Figure 14. Temperature distribution in flames emanating from a burning building [6]. The term, "fire load" refers to the weight of fuel per unit floor area of the involved structure.

fire department has told the author that it melts the tips off approximately 12 ladders per year.

4.1. Existing Standards

NFPA 193 has no requirement for high temperature performance.

ANSI A14.2 also has no requirement for high temperature performance. However, it does make reference to fire exposure:

> "Exposure to Fire - If ladders are exposed to excessive heat as in the case of fire, the strength may be reduced. After such exposure, the ladder should be inspected visually for damage and tested for deflection and strength characteristics. In doubtful cases, refer to manufacturer." (par A.2.6.2)

NFPA 193 requires that metal fire department ground ladders be made of aluminum alloy, a requirement that severely limits possible design improvements to provide high temperature strength. ANSI A14.2 contains no such restriction.

4.2. Existing Ladder Performance

Aluminum is desirable for light weight but its high temperature properties introduce an inherent limitation for fire department use. A volunteer fire company discovered this two years ago while fighting a serious fire in Maryland. An aluminum extension ladder was inadvertently exposed to direct flame contact during a fire. Within a matter of seconds, the ladder collapsed against the side of the building, unable to support even its own weight. A detailed study of this failure was made by the Metallurgy Division of the National Bureau of Standards. Their technical results are summarized in Appendix C. That study confirms that ladders made of aluminum will not withstand even brief exposure to elevated temperatures.

Raising the temperature of the ladder so high that immediate collapse or melting occurs is only one of the ways in which heat can damage aluminum. A second way is the much more subtle damage that can result from the phenomenon known as overaging. The aluminum alloy generally used in fire ladders (6061-T6) is a so-called age-hardenable alloy, which means that as a final step in its manufacture, it is placed in a furnace at 350 to 400°F (aging temperature) for approximately 10 hours. Such a heat treatment produces a structural change (called age-hardening) in the alloy that increases its yield strength to its final design value. However, the beneficial effect of this heat treatment can be dissipated by holding the alloy at its aging temperature too long or by heating it above the aging temperature. The higher the temperature to which the alloy is heated, the lower the yield and tensile strengths after it cools to room temperature; this is referred to as "overaging."

The effects of overaging are illustrated graphically in the heat treating curves shown in figure 15. Note that tensile strength drops rapidly with increasing exposure temperature and time. The decline is even more rapid at temperatures above 500°F, the highest temperature shown in the figure.

Thus properly heat-treated 6061-T6 aluminum has excellent properties at room temperature. But, as the above discussion of overaging shows, the room temperature properties of the alloy will be reduced after exposure to the kinds of temperatures that prevail around fires. For example, a ladder could easily be heated to temperatures around 400-600°F by exposure to radiant heat from a window or hot fire gases sweeping past it. This does happen in practice, since firemen tell of conditions where ladders had to be wet down with a hose to cool them. Under these conditions, the ladder may not show any visible signs of

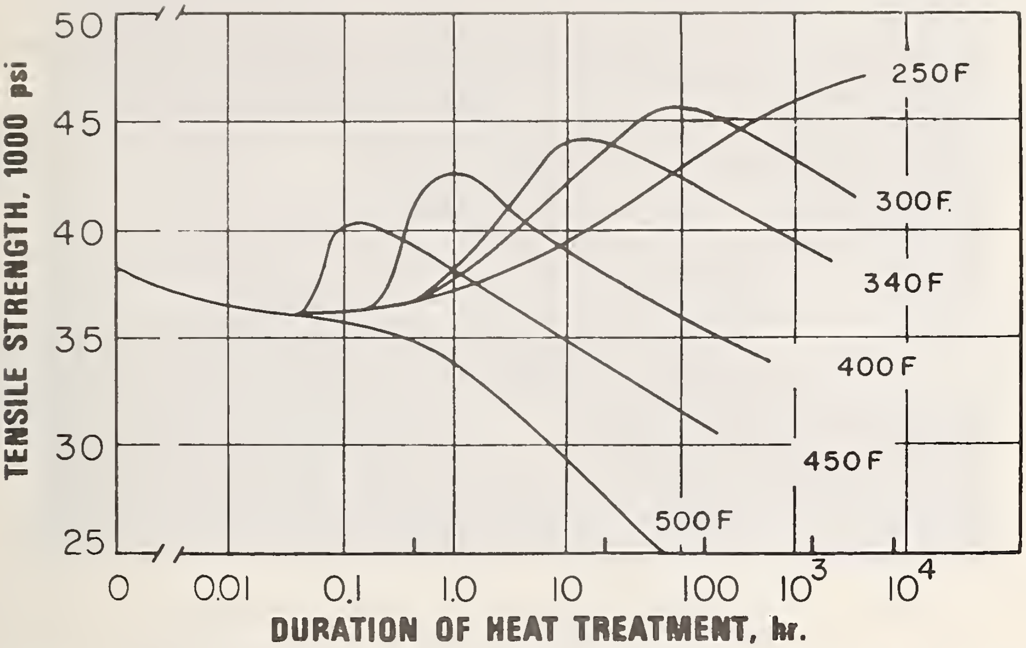

Figure 15. Heat-treatment curves for 6061-T6 aluminaum alloy, showing the rapid loss of tensile strength at elevated temperatures [7].

damage and may simply be cleaned up and placed back on the truck for use at the next fire. There is no way of detecting visually that such a ladder has been damaged and is now much weaker than before. This is a serious hazard and one against which minimum standards for ground ladders ought to provide reasonable protection.

One convenient way of detecting the deterioration of mechanical properties in the field is by the use of hardness tests. The use of a portable hardness tester to check the properties of an aluminum ground ladder is illustrated in figure 16. While it is widely recognized that hardness correlates roughly with tensile and yield strength, exact correlation has to be established experimentally for each particular alloy. Such a correlation has been performed at the National Bureau of Standards for the aluminum alloy 6061-T6 used in fire department ground ladders. The results of that work appear as Appendix D to this report.

4.3. Recommendations

Fire department ground ladders ought to perform satisfactorily under two types of high temperature exposure:

1. During brief exposure to high radiant heat loads or direct flame contact, the ladder should be able to support a substantial fraction of its design load.

2. After long term exposure to moderate heat levels, say, up to 600°F, the ladder should retain all of its room temperature strength.

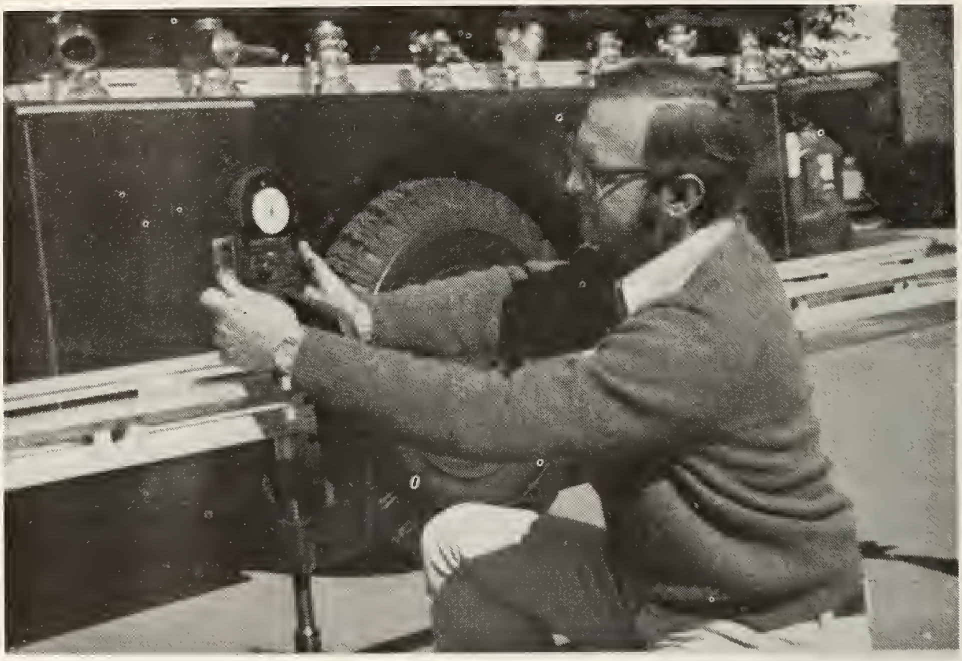

Figure 16. The strength properties of aluminum ladders may be checked non-destructively in the field by the use of a portable hardness tester, as demonstrated here.

Thus, existing minimum standards should be modified to incorporate two new performance tests. The exact nature of these tests requires further study. The following descriptions are meant only to suggest their general outline.

1. High temperature strength test. The ladder is set up in the same fashion as for the horizontal bending test used to determine load-carrying capacity. One half of the design load is placed at the mid-point of the fully extended ladder. A series of gas burners is placed directly above or below the ladder such that an area at least thirty-six inches in length and the entire width of the ladder is bathed in flame for one minute. In the case of single ladders, application of the flame shall be at the midpoint of the span. In the case of extension ladders, the flame shall be applied such that at least six but no more than 12 inches of the heated length shall include the overlap portion of the ladder, i.e. point of maximum stress (point F in figure 12b). The deflection of the ladder from the horizontal shall be measured before and after the application of the gas flame. If the deflection after flame application is less than twice that before flame application, the ladder will be considered to have passed the test.

2. High temperature aging test. The entire ladder is placed inside a furnace at 600°F for 1 hour, then removed, and air-cooled. When it has returned to room temperature, the load-carrying capacity, rigidity, and rung tests are repeated. The ladder must still be capable of passing the test for load-carrying capacity, the rigidity criterion must not have changed by more than 10 percent in either direction, and all rungs must pass the rung test criteria.

In addition, the requirement in NFPA 193 that fire ladders be made of aluminum alloy should be eliminated. This is extremely important because aluminum alloys are among the worst metals for high temperature strength.

Figure 17 shows the variation of tensile strength with temperature for several common metals. The 2024-T6 aluminum alloy shown in the figure is the best high temperature aluminum alloy available with high temperature performance considerably better than the 6061-T6 aluminum alloy of which most fire ladders are made. There are obviously a variety of materials with high temperature performance superior to that of aluminum.

Many fire service personnel erroneously believe that, to be light, a ladder must be made of aluminum or magnesium. This is not necessarily true because good design can often overcome the weight penalty imposed by a denser material.

5. WEIGHT

Weight is an important criterion in fire ladder selection. Since more manpower is required to erect a heavy ladder than a light one, volunteer departments and those that are undermanned generally prefer the lighter ladder. Of course, all fire departments benefit from having as light a ladder as possible to carry and set up.

5.1. Existing Standards

Neither NFPA 193 nor ANSI A14.2 make any mention of weight requirements.

5.2. Existing Ladder Performance

The total weights and weights per foot of extended length of several representative fire ladders are listed in table 4. The wooden ladder proves to be the heaviest while the aluminum ladders of manufacturer C are seen to be significantly lighter than those of manufacturer A.

Table 4. Relative Weights of Fire Ladders

Material	Manufacturer	Extended Length	Total Weight (lbs)	Weight per Foot of Extended Length (lb/ft)
Aluminum	A	23' 6"	62	2.6
Aluminum	A	30' 10"	118	3.8
Aluminum	A	35' 6"	133	3.8
Aluminum	B	19' 10"	62	3.1
Aluminum	C	19' 11"	47	2.4
Aluminum	C	30' 3"	85	2.8
Aluminum	C	34' 9"	118	3.4
Wood	D	37' 0"	157	4.2

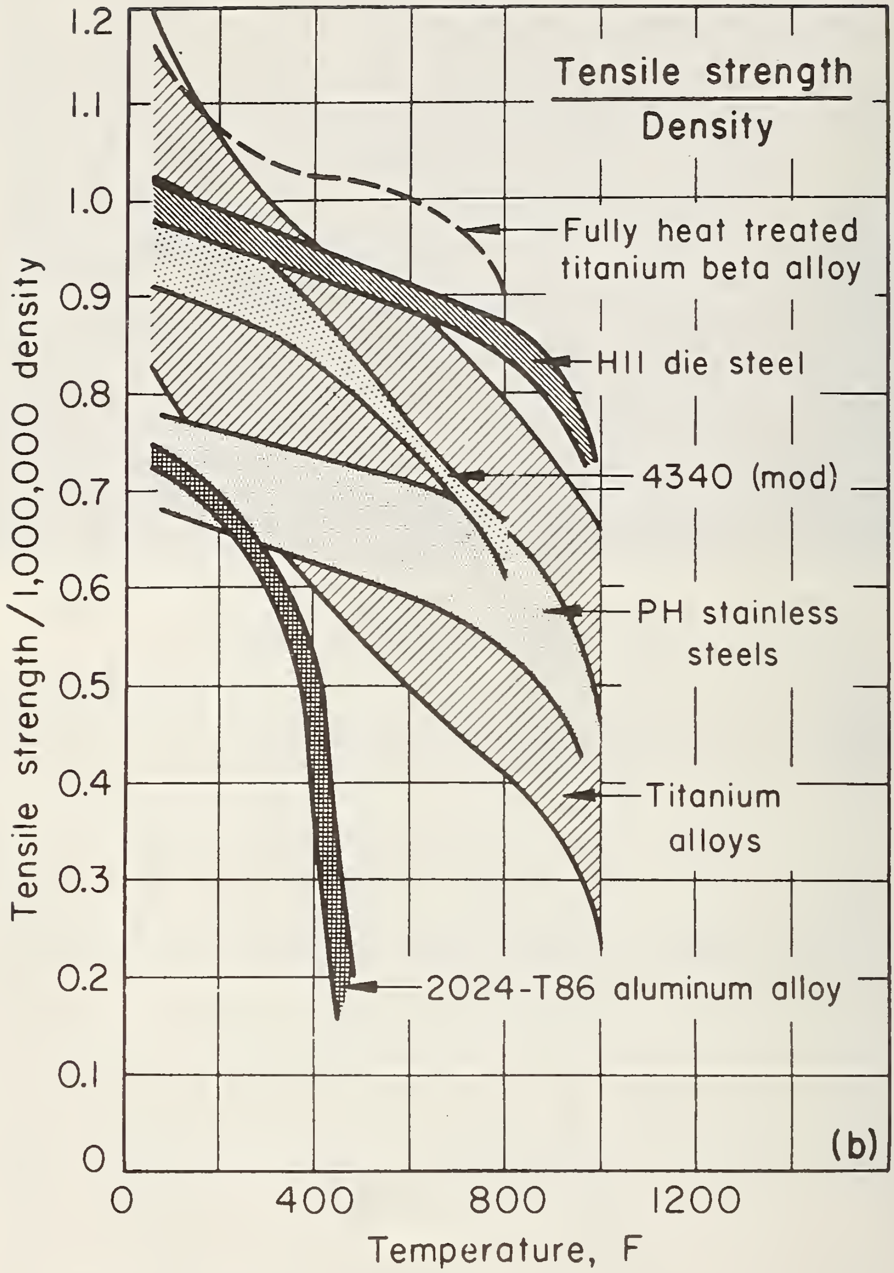

Figure 17. Comparison of the strength-to-weight ratio with temperature for several common metals (8). Note the rapid drop in the aluminum alloy properties above 200°F.

5.3. Recommendation

Several categories of weight classification could be incorporated into a fire ladder standard. A suggested weight classification scheme follows:

Class	Weight Range (per foot of extended length)
A	Less than 2.0 lb
B	From 2.0 to 2.5 lb
C	From 2.5 to 3.0 lb
D	From 3.0 to 3.5 lb
E	From 3.5 to 4.0 lb
F	More than 4.0 lb

6. STIFFNESS

By stiffness is meant the extent to which a ladder deflects under load (figure 18). The less stiff the ladder, the more it tends to bounce and shake in use. Too much bounce and shake can be unnerving and dangerous. Many fire chiefs seem willing to tolerate an increase in weight in return for greater stiffness.

6.1. Existing Standards

NFPA 193 contains no requirements for stiffness.

ANSI A14.2 does include a stiffness requirement under the heading, Deflection Test (par 6.1.6). The test arrangement is shown schematically in figure 19. A 60 pound load is hung from one rail of the single ladder or fully extended extension ladder at the center of the span. The resulting mid-span deflection and the angle α (figure 19b) are measured and compared with maximum permissible values. The latter are presented in a table for various size ladders, some of which are listed below:

Extension Ladder Size (ft)	Max. Deflection (in)	Max. α (degrees)
20	3.1	3.6
24	3.8	4.7
32	5.6	5.7
36	6.8	6.1

The purpose behind measuring α is presumably to measure the extent to which the ladder redistributes an eccentrically applied load to both side rails. It thus provides some measure of the lateral stiffness of the ladder in the presence of an unevenly applied load.

The extent to which a ladder resists the application of a load from the side is also evaluated in ANSI A14.2 by the so-called "Side Sway Test" (par 6.1.7). The ladder is placed on edge resting on level supports 6 inches from each end. The sections of extension ladders are tested individually. When a 60-pound load is applied at the mid-point of the lower rail, the maximum deflection may not exceed certain maximum permissible values listed in a table, some of which are listed below:

Section Length (ft)	Maximum Allowable Deflection (in)
10	1.25
12	1.50
14	1.75
16	2.00
18	2.25

Figure 18. Deflection of a three-section ladder with two men on it.

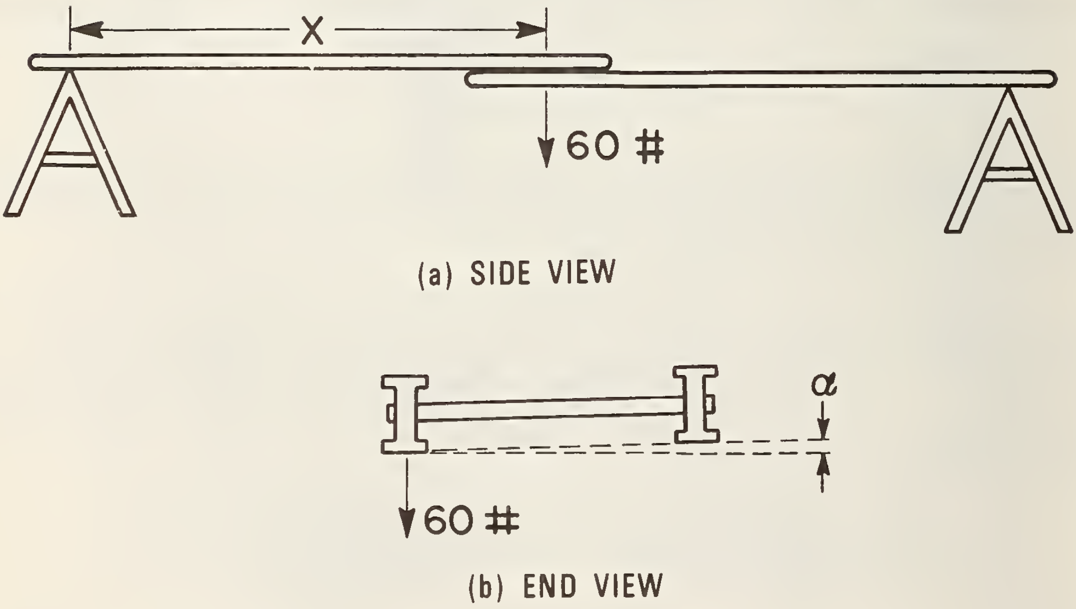

Figure 19. Schematic representation of the American National Standard Institute Deflection Test.

6.2. Existing Ladder Performance

The National Bureau of Standards has tested the stiffness of several fire department ground ladders using a scheme that differs from that utilized in ANSI A14.2 in that the load was applied equally to both side rails. The results of these tests are shown in figure 20. The results are plotted in terms of bending moment which is simply the product of 1/2 the applied load and 1/2 the span of the ladder (X in figure 19). For example, a 60 pound load applied to the mid-point of a 24 foot ladder (3-foot overlap) produces a bending moment of 300 ft-lbs. The steeper the slope in figure 20 for ladders of a given size, the less stiff the ladder.

The National Bureau of Standards has also tested the transverse bending of fully extended ground ladders. The results are shown in figure 21.

6.3. Recommendations

The deflection and side sway tests of ANSI A14.2 should be incorporated into the minimum standard for fire ladders. However, instead of setting one minimum requirement for all ladders, several classes of performance could be set up and ladders rated for stiffness according to the class in which they fall. At least one class should specify stiffness in excess of that of the stiffest ladder presently available.

The twist requirement (α factor) that is a part of the American National Standard needs to be critically evaluated in light of fire department usage. It is, for example, often not possible for fire departments to place ladders such that both rails of the unloaded ladder are firmly supported at the top. Under those circumstances, it is desirable that the ladder twist under relatively light loading so as to provide a firm footing for an ascending and descending fireman. The kind of twisting that a ladder must undergo in these circumstances is illustrated in figure 21. Thus it may be appropriate to require a fire ladder to display some minimum α as well as the maximum α now required. Further study and analysis is needed before such a range can be specified.

7. RESISTANCE TO LOCAL IMPACT

Ladders used by fire departments typically undergo rough handling. They may be accidentally struck by axes, falling objects, etc.; they may be dropped, or they may be blown down by the wind. It is important that fire department ladders be able to withstand such abuse, from the standpoint of both safety and economics (i.e. the cost of replacement or repair). A bent side rail can drastically reduce the strength of a ladder.

An extreme example of impact damage to a fire ladder is shown in figure 22 The collapse of a wall of a heavily involved building resulted in the badly bent ladders shown in the figure; several firemen were killed in the accident.

7.1. Existing Standards

NFPA 193 has no requirement for resistance to impact. It does, however, acknowledge the fact that impact damage to a ladder can easily occur and that it has serious consequences: "Ladders can be damaged during removal from the truck as well as during replacement on the truck . . . . Sometimes this is done carelessly, the shorter ladders being thrown to the ground or against sharp-edged curbing or other objects which may cause serious damage. Use care in removing ladders, placing those not needed immediately in a safe position where they cannot be injured." (par 112)

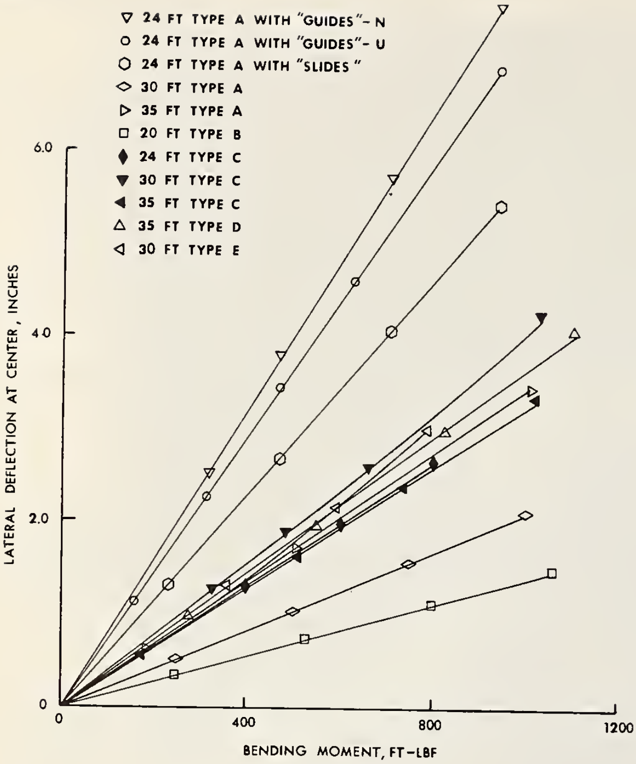

Figure 20. Deflection vs. Bending Moment for several ground ladders.

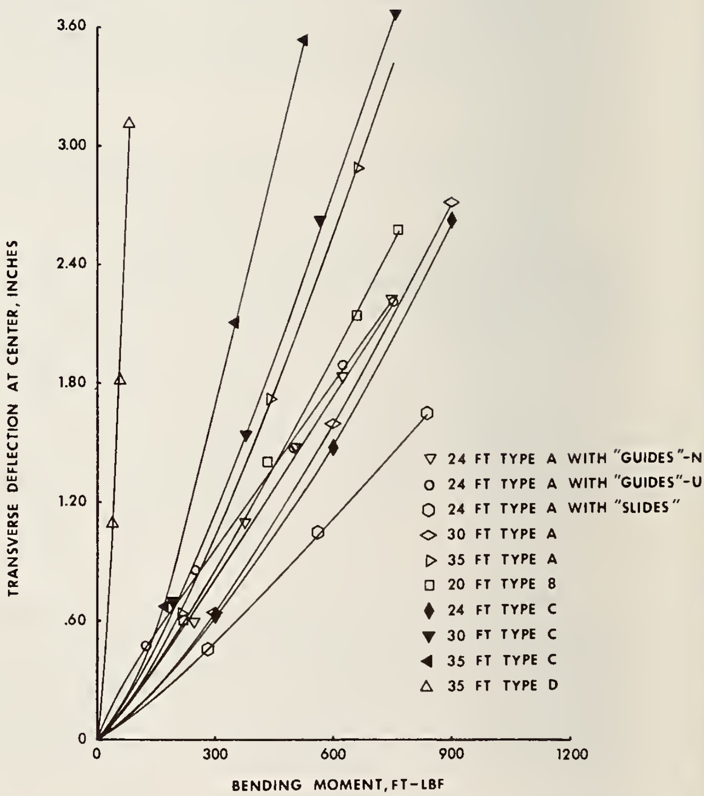

Figure 21. Transverse Deflection vs. Bending Moment for several ground ladders.

Figure 22. A falling building wall produced the damage shown to these ladders.

ANSI A14.2 also has no requirement for resistance to local impact. Like the NFPA standard, it assigns to the user sole responsibility for avoiding this kind of damage. "Ladders, like any tool, must be handled with care and not subjected to unnecessary dropping, jarring, or misuse." (par A2.1) [After tipping over], "inspect ladder for side rail dents or bends, or excessively dented rungs . . . . " (par A2.6.1). "Ladders having defects are to be marked and taken out of service until repaired. Never straighten or attempt to use a bent ladder." (par A2.7) "Never climb a damaged ladder." (par A3.6)

7.2. Existing Ladder Performance

No systematic testing has, to the author's knowledge, ever been undertaken to evaluate a ladder's resistance to local impact. However, the resistance of side rails to deformation applied at low strain rates would be expected to be proportional to their resistance at high strain rates and this property has been measured in tests conducted at the National Bureau of Standards. A load was applied at a constant slow rate to the upper beam of a trussed ladder, midway between the rungs, as shown in figure 23. Load and deformation were continuously recorded in order to determine the load at yield (0.2% offset) and the maximum load sustained.

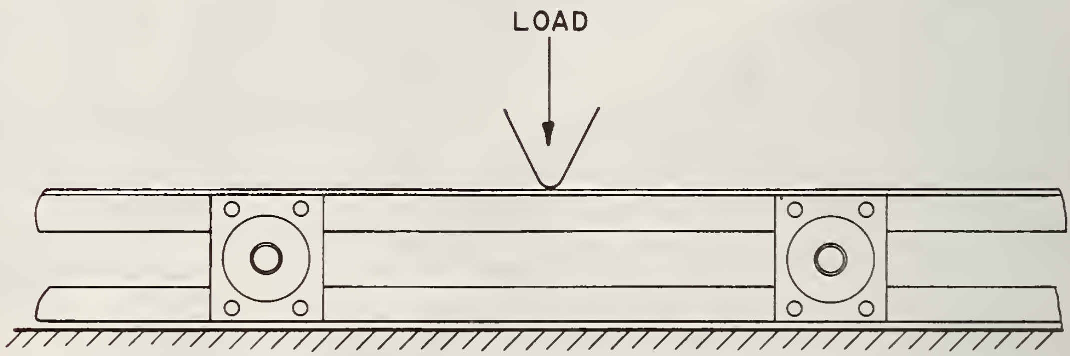

Figure 23. Method of measuring resistance of ladder side rails to bending.

The results of tests on two manufacturers' ladders are shown in table 5. Clearly, there is a significant difference in their performance. Such a difference could also be expected, were the load to be applied at some higher strain rate, more nearly characteristic of impact loading.

Table Ability of Ladder Rail to Sustain Load Between Rungs

Manufacturer	Type	Load at Yield[a] (0.2% offset)	Maximum Load[a]
A	35-foot, 2-section	2,110 lbs	3,110 lbs
C	24-foot, 2-section	1,115 lbs	1,420 lbs

[a]Each number represents an average of 2 tests on 2 rails of the same ladder.

7.3. Recommendations

Firemen, working under emergency conditions, cannot always exercise care in handling ladders. Therefore, it is desirable that ladders be designed to provide reasonable protection from local impact loading. A criterion for resistance to local impact should be included in a standard for fire department ground ladders. A suitable test method using a pendulum or a dead-weight drop test should be developed. A series of performance classes is preferable to a single minimum requirement and would be in keeping with similar schemes suggested in this report for other ladder properties.

8. RUNGS

Rungs serve several purposes: (1) they support the climber, (2) they provide a connection between the side rails, and (3) they permit a fireman to establish a leg-lock (figure 24).

8.1. Existing Standards

NFPA 193 specifies that rungs be 14 inches apart (par 103) while ANSI A14.2 specifies 12-inch centers ±1/8" (par 4.3). No reason for this difference is apparent; possible explanations are that wider spacings on the fire ladder mean fewer rungs and therefore less weight or that the wider spacing is needed to permit a fireman's leg-lock.

NFPA 193 specifies rung construction: "Rungs shall be constructed of heavy duty corrugated aluminum not less than 1 1/4 inches in diameter" (par 103). ANSI A14.2 contains no restrictions as to rung materials or dimensions and states that rungs shall be either "corrugated, serrated, knurled, dimpled, or coated with skid-resistant material". (par 4.5)

Both standards include a twist test. In NFPA 193 (par 133), a 350 in-lb torque is applied once to each rung by means of a clamped lever arm. Any relative motion between rung and side rail necessitates rung replacement. The ANSI A14.2 twist test, called the Rung Torque Test (par 6.1.5), is far more demanding. A torque of 900 in-lb is applied 20 consecutive times in alternate directions to each rung. Relative motion between rung and side rail disqualifies the rung.

Both standards also include a strength test. In NFPA 193, a 450 pound load is applied along a 4-inch length at the center of the rung. Permanent deflection at the center of the rung must not exceed 1/16 inch. Again ANSI

Figure 24. Fireman demonstrating leg-lock on a ladder.

A14.2 is considerably more demanding. For its Rung Bending Strength Test (par 6.1.3), a 1000 lb load is applied to a 3 1/2-inch wide portion of the center of one rung. Permanent deformation in excess of 1/100 of the rung length is not permitted.

ANSI A14.2 includes two additional tests not found in NFPA 193. The Rung to Side Rail Shear Strength Test (par 6.1.4) is identical to the Bending Strength Test except that the criterion for failure is "indication of failure either in the fastening means attaching the rung or the side rail." The Side Rail Cantilever Bending Test (par 6.1.8) applies a 200 pound axial load for one minute to one side rail while the other is held clamped; the criterion for failure is "visible defects or permanent deformation."

8.2. Existing Ladder Performance

Some fire service personnel with whom the author has spoken have questioned the appropriateness of the 14-inch rung spacing. A Government-sponsored study of human factors problems in firefighting equipment [5] pointed out that "there have been observations made by the firemen that the rungs on the ladder are either too far apart or too close." Elsewhere, the same report suggests that "The distance between the rungs of the ladders should take the size of the firemen into account. Since most ladder operations are done by blind reach, it could be important that the rungs of the ladders are correctly spaced to accommodate climbing or descending." To the author's knowledge, no study of this design problem has ever been conducted.

Rungs do not otherwise appear to be causing firemen any serious problems. However, the previously cited report [5] also points out that "the rungs on the ladder can become slippery from water and oil, ice or other foreign materials."

8.3. Recommendations

A systematic study of optimum rung spacing would be desirable.

The NFPA requirement specifying the construction material and diameter of rungs is restrictive and should be deleted. As discussed previously, aluminum has insufficient high temperature strength which limits its suitability as a material for fire ladders.

The ANSI Rung to Side Rail Shear Strength Test and Side Rail Cantilever Bending Test should be included in a fire department ground ladder standard. In addition, the present NFPA rung torque test and bending strength test should be upgraded to the higher performance called for by the American National Standard.

Finally, a study might be conducted of possible ways to combat the slipperiness of rungs due to water, oil, ice, or other materials.

9. HARDWARE

While neither ANSI A14.2 nor NFPA 193 define the term, "hardware," it is used here to describe all components of a ladder other than rungs and side rails. Thus, it includes the rivets used to hold the ladder together, rope and pulley guides, and locking devices (frequently referred to as "dogs" or "pawls") on extension ladders, safety shoes, staypoles, and hooks.

9.1. Existing Standards

NFPA 193 makes extensive references to various hardware items but the requirements are for the most part qualitative and vague. NFPA hardware requirements are listed below with the author's comments:

> "Provisions shall be incorporated in the side members to prevent ladder sections from becoming disengaged during use." (par 102) Unfortunately, no test is provided for evaluating this characteristic.
>
> "All riveting or welding should develop strength equal to the side members." (par 103, sentence 3)
>
> "Ladder locks or pawls on extension ladders shall be so fastened or secured to the beams that vibration and use will not cause loosening of bolts and nuts. Pawls or ladder locks shall be so constructed that the hook portion of the pawl shall have sufficient bearing surface or area to prevent hook from cutting into rungs when engaged. Such hooks shall be properly finished to eliminate sharp edges and points." (par 104)
>
> "Staypoles shall be furnished on all extension ladders extending over 36 feet. Staypoles will be furnished detachable only if specified by the customer. Staypole spikes shall not project beyond the end of the ladder when nested." (par 105) There is no mention of minimum strength requirements for staypoles nor is any suitable test method specified in either the NFPA or the American National Standard.
>
> "Rope used for raising extension ladders shall be Class I quality Manila rope. On three-section ladders the third section may be extended by wire rope." (par 106)

"Roof ladders shall be provided with folding type hooks of sufficient strength to carry imposed loads. Hooks shall be securely fastened to beams. Hooks shall support a load of 500 pounds." (par 107) This requirement is inadequate for two reasons. First, there is no statement as to how the load is to be applied, i.e. at the point of the hook, at some other point along its length, or as a distributed load along its length. Secondly, a 500 pound strength requirement is too low for a ladder rated to support a man on every other rung (see section 3 above).

"There shall be placed on the butt or base end of each beam of the main ladder of extension ladders, and on the butt or base of each beam of wall and roof ladders a metal reinforcement. This shall be butt spurs or other suitable means to prevent ladders from slipping when in place." (par 108)

ANSI A14.2 also makes numerous recommendations on hardware:

"Hardware shall meet strength requirements of the ladder's component parts, and shall be of a material that is protected against corrosion unless inherently corrosion-resistant. Metals shall be so selected as to avoid excessive galvanic action." (par 4.6)

"All workmanship shall be free from burrs in excess of 1/64 inch. Bolt and rivet holes are to be accurate and within tolerances of good commercial metal working practices. Rivets are to be set properly and are to be free of structural defects. Welds are to be of commercially accepted practices and free of defects." (par 4.7)

"Extension ladders shall be equipped in such a manner that the ladder cannot be used with an overlap less than the minimum specified in table 2." (par 5.2.6)

"The extension locking device shall be designed to withstand all load tests. Locks may be gravity or spring-action types to engage the rung of the base section or the base section rung and the mating fly section rung. A fly section incorporating stationary lock, or locks, which by their location eliminate a rung in the section shall include a permanent marking in letters not less than 1/8-inch high: "Caution - This Ladder Section is Not Designed for Separate Use" or permanently attached stops shall be provided to prevent removal of the fly section. Permanently attached stops are considered those that would require cutting or drilling for removal." (par 5.2.7)

"Extension ladders may be equipped with a rope and pulley. The pulley shall be attached to the ladder in such a manner as not to weaken either the rungs or the side rails. The pulley shall be not less than 1 inch in diameter measured at the base of the sheave." (par 5.2.8.1)

"The rope used with the pulley shall be not less than 1/4 inch diameter, having a minimum breaking strength of 560 pounds, and shall be of sufficient length for the purpose intended. On three section ladders, where cable is used in a rope and pulley hook up, the cable may be 3/16 inch in diameter." (par 5.2.8.2)

In addition to these descriptive requirements, ANSI A14.2 includes a hardware test requirement for heavy duty extension ladders. (par 6.1.2.1) The fly section is extended at least one rung and, with the ladder in a vertical position, a 1000 pound load is applied axially. The ladder must withstand this load without permanent deformation or other visible weakening. This test would appear to be mainly a test of the extension locking device, and not of any of the other hardware items.

9.2. Existing Ladder Performance

The author is unaware of any tests conducted specifically for the purpose of evaluating ground ladder hardware. However, some of the horizontal bending tests conducted by the National Bureau of Standards and described above (table 3 produced initial failure at the hardware rather than in a structural member. An example is shown in figure 25.

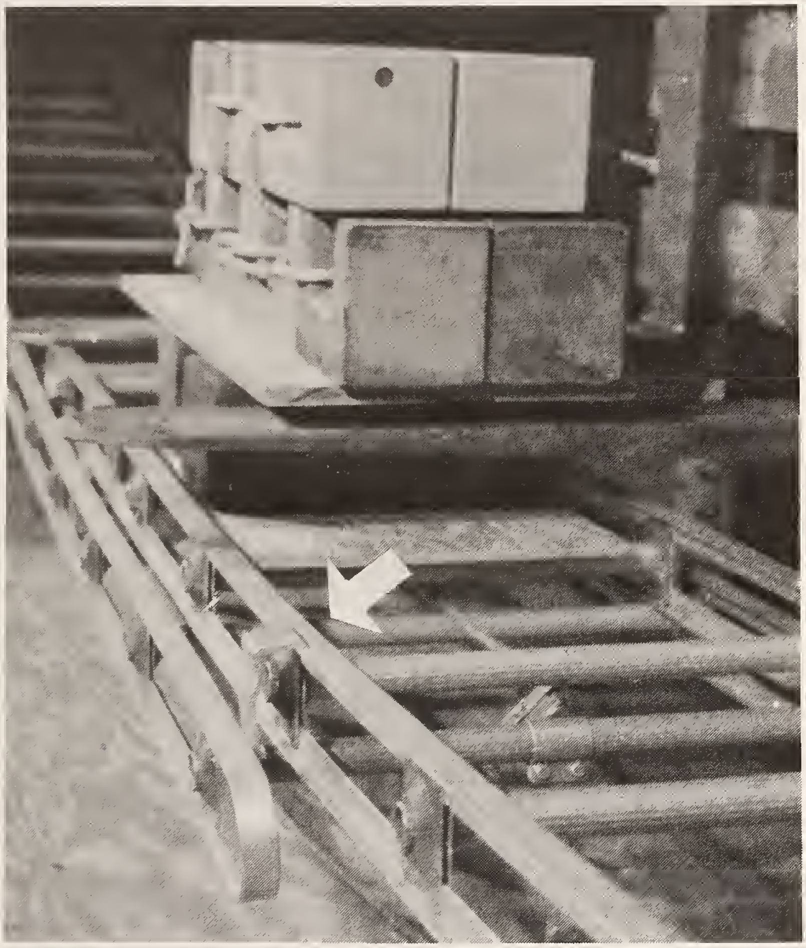

Figure 25. A ladder undergoing test about to give way at a guide (arrow).

9.3. Recommendations

Generally speaking, it should not be necessary to specify special mechanical tests for hardware items. If suitable mechanical tests are developed for the ladder as a whole, these tests will show up any shortcomings or deficiencies in the hardware. The only exceptions will likely be the rope and pulley, extension ladder stop, and safety shoes.

The more stringent hardware requirements of ANSI A14.2 should be incorporated into the standard for fire department ground ladders. In addition, study should be initiated to insure adequate test procedures for hardware items with particular emphasis on roof ladder hooks, staypoles, and safety shoes.

10. SUMMARY

The performance of fire department ladders can only be improved if the performance requirements are clearly understood. An essential first step is the upgrading of existing voluntary standards to reflect accurately the performance demands likely to be made on these ladders.

The existing voluntary standard for fire department ground ladders (NFPA No. 193-1972) can be upgraded quickly by incorporating in it many of the performance requirements or test procedures listed in American National Standard A14.2 for heavy duty straight and extension ladders. Specifically, the following ANSI A14.2 requirements are recommended for inclusion in NFPA 193:

1. Width (par 5.2.1 and 5.2.2)

2. Load-carrying capacity, including heavy duty rating (sec. 3), and horizontal bending test (par 6.1.1).

3. Stiffness, including deflection test (par 6.1.6) and side sway test (par 6.1.7).

4. Rungs, including rung bending strength test (par 6.1.3), rung to side rail shear strength test (par 6.1.4), rung torque test (par 6.1.5), and side rail cantilever bending test (par 6.1.8).

5. Hardware, including general requirements (par 4.6, 4.7, 5.2.6, 5.2.7, 5.2.8.1, and 5.2.8.2) and hardware test. (par 6.1.2.1)

Besides these additions, certain unnecessarily restrictive requirements ought to be dropped from NFPA Standard 193. Principal among these is the requirement that metal ladders be made out of aluminum alloy. Also, the sizing requirement presently described in NFPA Standard 19 ought to be made more explicit and incorporated in NFPA 193.

But even with such upgrading of the present standard, deficiencies remain. These can, however, be corrected after further study and analysis have clarified the following needs:

1. Width. Appropriate widths for fire ladders ought to be based on how firemen use ladders, stability requirements, and weight and space restrictions.

2. Load-carrying capacity. Test methods are needed that go beyond the simple horizontal bending test in simulating the loads firemen place on ladders.

3. High temperature tests. New test methods are needed to evaluate a ladder's resistance to exposure to the heat of the fire.

4. Weight. While an important criterion for ladder selection and an important consideration in manning and set-up time, weight is omitted from present standards.

5. Stiffness. Better criteria are needed for evaluating the stiffness of ladders in fire service use.

6. Resistance to local impact. This is an especially important consideration for ladders used under emergency conditions, particularly since a damaged ladder is usually an unsafe ladder.

7. Rung spacing. It should be optimized for ease of climbing, human factors, and minimum weight.

8. Hardware. All ladder test methods should be designed, as far as practical, to test hardware and structural members simultaneously. For such items as roof ladder hooks, staypoles, and safety shoes, special test methods may be needed.

To the maximum extent possible, ladder test methods should utilize simple equipment, likely to be available or readily obtainable in a fire station. Where this is not possible, e.g. the high temperature tests, equipment and procedures should still be kept as simple as possible.

This report has pointed out the shortcomings of fire department ground ladders and applicable standards, while offering suggestions for improving the latter. The following quotation from a letter sent to the author by one of the major ladder manufacturers offers a fitting conclusion to this study:

> "We, as manufacturers of aluminum fire ladders, welcome the institution of and need a set of fire ladder standards which would apply industry-wide and feel that you will concur with our statement that NFPA-193 is sadly lacking in useful information."

APPENDIX A. LADDER FAILURE A

A number of pieces from a 35 foot, two section, aluminum fire ladder, owned by a fire department, which had failed in service were examined by Mr. T. Robert Shives, metallurgist in the Mechanical Properties Section, Metallurgy Division of the National Bureau of Standards to determine the following:

1. Whether the submitted material consisted of properly heat treated aluminum alloy 6061-T6.

2. The origin of the small cracks along the edges of the member labeled "top rt. rail, bed section."

3. The likely cause of failure.

4. Tensile strength of failed rail material.

According to representatives of the fire department, failure occurred under the following circumstances. A fireman became incapacitated while working at the top of a fully-extended 35 foot aluminum ground ladder. When a second fireman ascending the ladder to assist him reached approximately the tenth rung from the bottom, the ladder abruptly collapsed against the building reportedly injuring seriously the fireman at the top of the ladder. The situation immediately prior to failure is shown schematically in figure A-1. There appears to have been a hose line in use on the ladder at the time of failure; this has not been shown in the sketch. A photograph of a portion of the failed ladder taken at the scene of the accident is shown in figure A-2.

Figures A-3a and A-3b show the pieces of the ladder as received by the National Bureau of Standards. The T-members of the rails and the end cap are designated as follows:

NBS Designation	Piece Description
A	Top right rail, bed section
B	Top left rail, bed section
C	Lower right rail, bed section
D	Lower right cap, fly section
E	Lower left rail, bed section

A.1. Visual and Macroscopic Examination

As shown in figure A-2, the bed section of the ladder failed just below the fifth rung from the top. This was at the approximate location of the bottom of the fly section. All T-members of the bed section except for E had fractured. All four T-members had deformed to a considerable extent indicating good ductility and yielding before fracture.

Examination of the fracture surfaces indicates failure from overload.

The ladder was being used within the load carrying limits specified in NFPA 193 [2]. According to paragraph 132 of that standard, a trussed extension ladder of length 26 to 35 feet can support up to four men when placed with "The butt of the ladder at a distance not to exceed one-third the ladder length away from the building . . . . At angles less than these the load limit on the ladder will decrease accordingly." Since the ladder was placed at a somewhat longer distance from the building (see figure A-2), it is necessary to calculate a reduced load limit from geometric considerations (see eqs (1) and (2) in section 3). This works out to a 2.75-man load limit. Thus, the 2-man load reportedly applied was within the rated capacity of the ladder, as defined in NFPA 193.

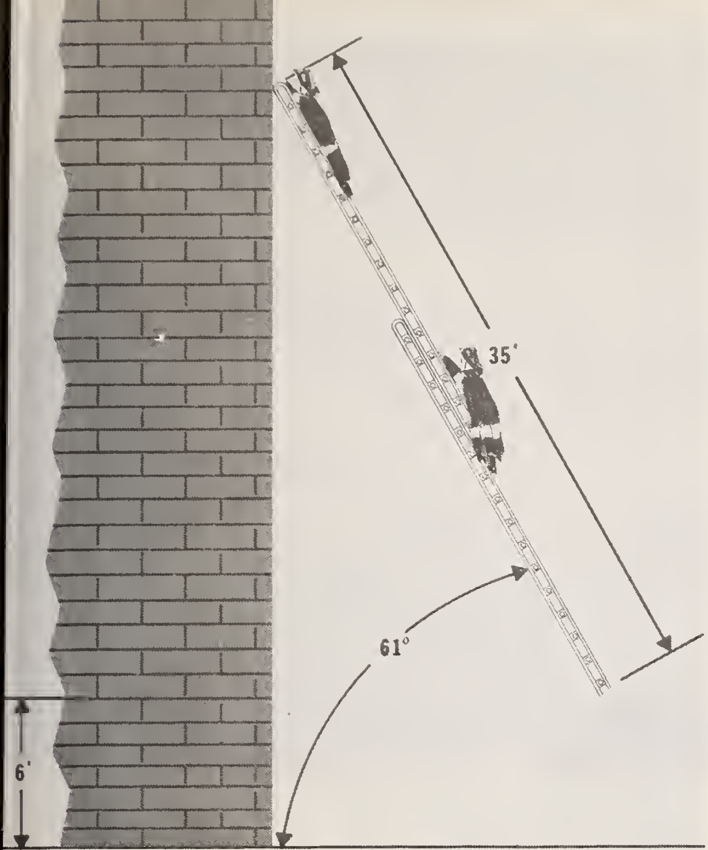

Figure A - 1. Sketch of ladder immediately prior to failure, as reported by fire department.

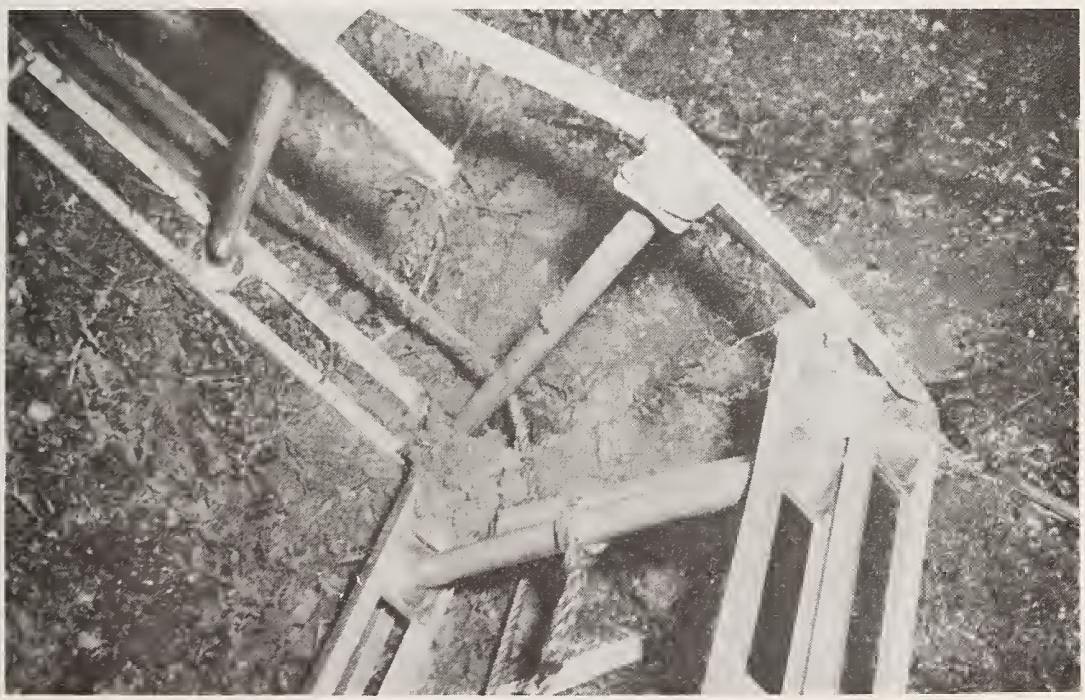

Figure A - 2. Failed portion of ladder immediately after failure. Photograph taken at scene.

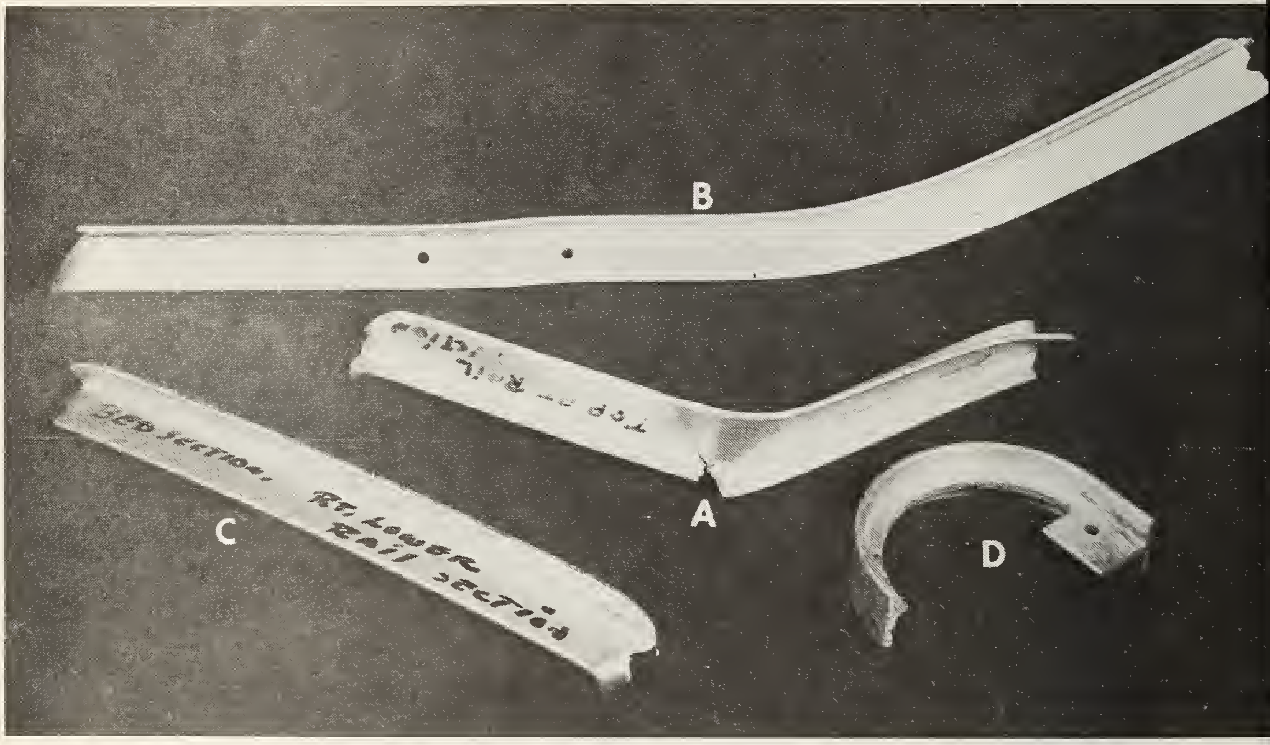

Figure A-3a. Ladder parts as received. X 1/2

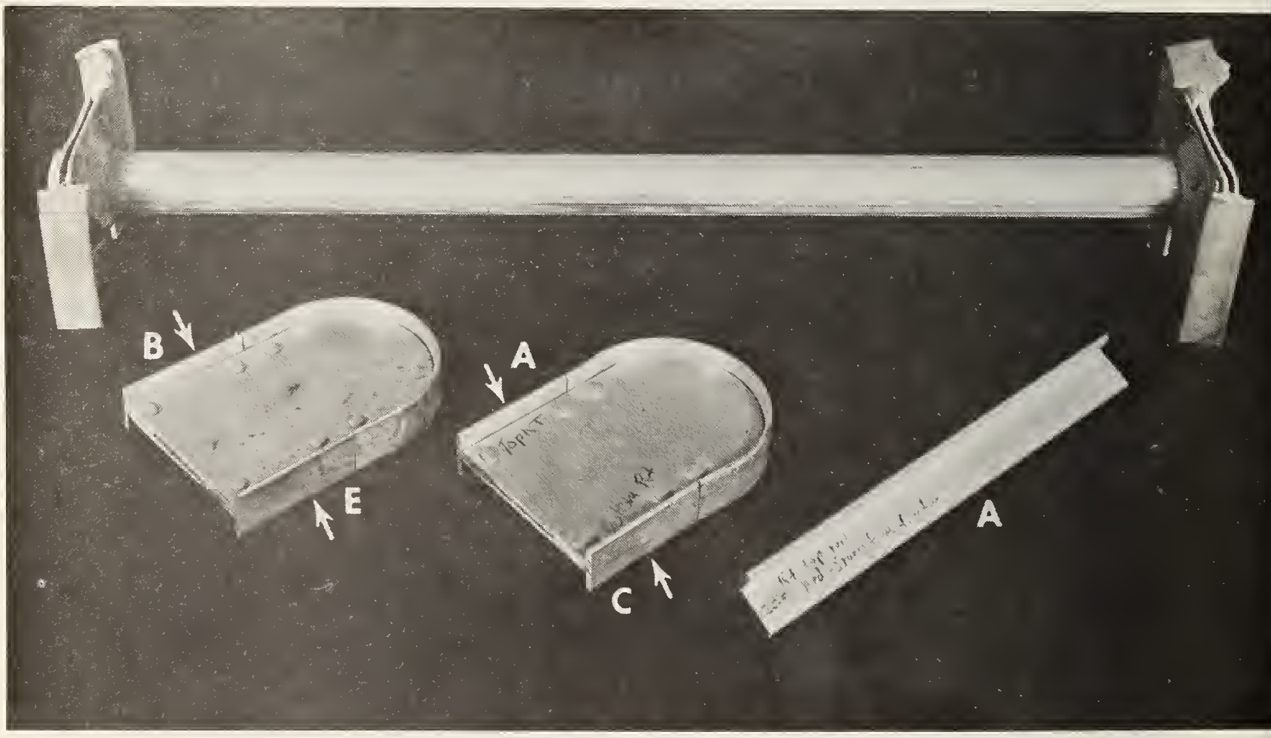

Figure A-3b. Ladder parts as received. X 1/3

The submitted members were examined for cracking along the edges with the following results:

Member	Location	Observations
A	adjacent to fracture	numerous cracks exist at both edges of flange and at edge of stem
	adjacent to upper end cap	cracks exist at both edges of flange, but none observed on stem
	about five rungs below fracture	cracks observed at one flange edge only
B	adjacent to fracture	no cracks
	adjacent to upper end cap	no cracks
C	adjacent to fracture	cracks observed at both edges of flange, but to a lesser extent than in A; no cracking at edge of stem
	adjacent to upper end cap	cracks observed on one flange edge only
D		no cracks
E	adjacent to upper end cap	no cracks

The cracks mentioned above in piece A are shown in figures A-4 and A-5.

The T-members are extruded. It appears most likely that the cracks in pieces A and C occurred during the extrusion process rather than when the ladder was in service. Cracking and even complete disintegration can occur during extrusion of the aluminum alloys if the rate of extrusion is too high resulting in excessive temperatures [9]. Some of the fractures went through these cracks (figure A-6), but it does not appear that the fractures started at these cracks.

A.2. Chemical Analysis

A sample from piece C was analyzed by the NBS Analytical Chemistry Division. The specified composition for aluminum alloy 6061 and the results of the NBS analysis are given below.

Element	Specification	Analysis
Si	0.40 - 0.8%	0.53%
Fe	0.7 max	0.20
Cu	0.15 - 0.40	0.18
Mn	0.15 max	<0.02
Mg	0.8 - 1.2	0.88
Cr	0.04 - 0.35	0.08
Ni		<0.02
Zn	0.25 max	<0.02
Ti	0.15 max	0.05

Figure A-4. View of member A showing cracks at the edge of the flange near fracture X 7.

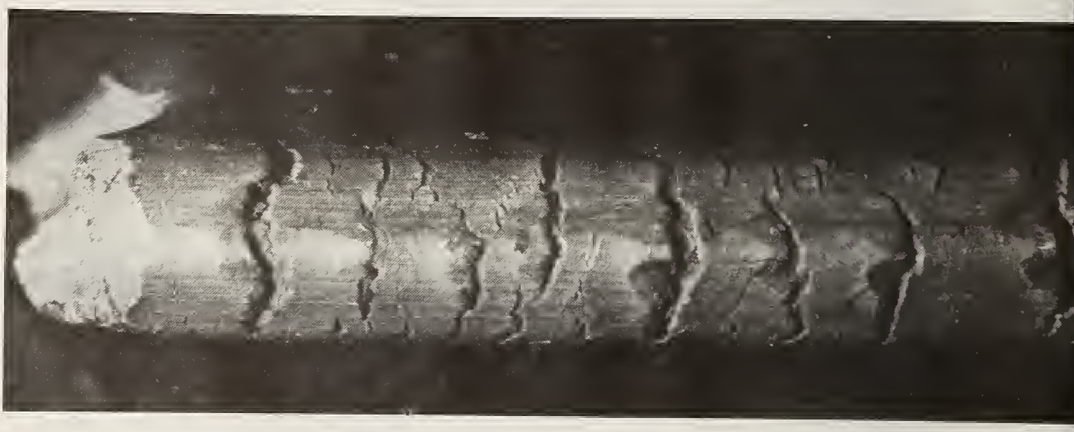

Figure A-5. Cracks at the edge of the flange in membe A adjacent to fracture. X 10

Figure A-6. Fracture surface member A. This fracture went through extrusion crack (left). X 10

The material meets chemical composition requirements for aluminum alloy 6061.

A.3. Thickness Measurements

Thickness measurements were made on five ladder members close to the area of fracture, but not where the section thickness had been affected by the deformation.

Member	Thickness Flange (in)	Stem (in)
A	.124	.114
B	.127	.116
C	.123	.114
D	.129	.121
E	.124	.115

A.4. Hardness Measurements

Rockwell B hardness measurements were made on the various members as follows. Each value reported is an average for three measurements.

Member	Location	R_B Hardness Flange	Stem
A	adjacent to fracture	30.8	30.0
	adjacent to upper end cap	20.5	23.7
	about 5 rungs below fracture	30.3	31.8
B	adjacent to fracture	55.3	52.7
	adjacent to upper end cap	47.2	51.5
C	adjacent to fracture	49.2	50.7
	adjacent to upper end cap	48.3	50.5
D		54.0	55.3
E	adjacent to upper end cap	19.7	25.0

The acceptable R_B hardness range for aluminum alloy 6061-T6 is 47-72 [10].

The hardness of members B, C, and D indicates that this material is in the T6 temper condition. Members A and E are too soft to be in the T6 temper; they are in the hardness range of the T4 temper (acceptable range approximately R_B 19-45) but this hardness could have been developed either by tempering to T4 or by softening material in the T6 temper by heating it. If the material is in the T4 temper, it could have a yield strength as low as one half the yield strength of material in the T6 temper.

A piece of the soft material from the ladder was solution treated and artificially aged to produce the T6 temper. The hardness was R_B 62.5. A piece of material in the T6 temper was solution treated and aged at room temperature. After 7 days the hardness was R_B 18 which is just about at the T4 temper. This shows that if properly heat treated, the soft material will develop a hardness in the T6 range. Also by reheat-treating a piece of the material in the T6 temper and naturally aging it, the T4 temper can be obtained.

A.5. Microscopic Examination

Metallographic examination of sections from the various members indicates that the material is relatively free of inclusions. Figure A-7 shows an unetched transverse section from member A which is typical for the sections examined. Figures A-8 and A-9 show the microstructure in transverse sections through members A and B, respectively. There are a large number of very small grains in the section through B, but there is very little difference in average grain size among the four sections examined. The ASTM grain size is as follows:

Member	ASTM Grain Size
A	6 1/2
B	7
C	6
E	6 1/2

Since members A and E, which are softer than the other members, have a grain size no greater than members B and C, there has been no apparent grain growth in A and E. This material, therefore probably has not been subjected to excessive temperatures for any length of time.

Longitudinal sections through the flanges of the T-members show essentially no grain elongation and no gross differences in grain size across the section, but some variation in grain size among different areas of a given section. Figures A-10 and A-11 show the structure in longitudinal sections through A and B, respectively.

Figure A-7. Transverse section through member A which is typical of those sections examined. Unetched. X 100

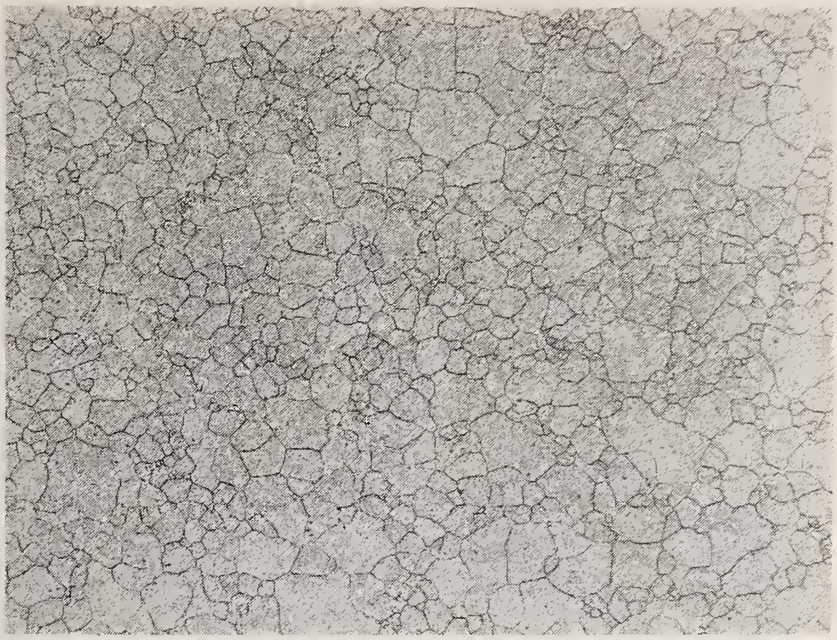

Figure A-8. Microstructure of transverse section through member A near fracture. Etch: 10% sodium hydroxide. X 100

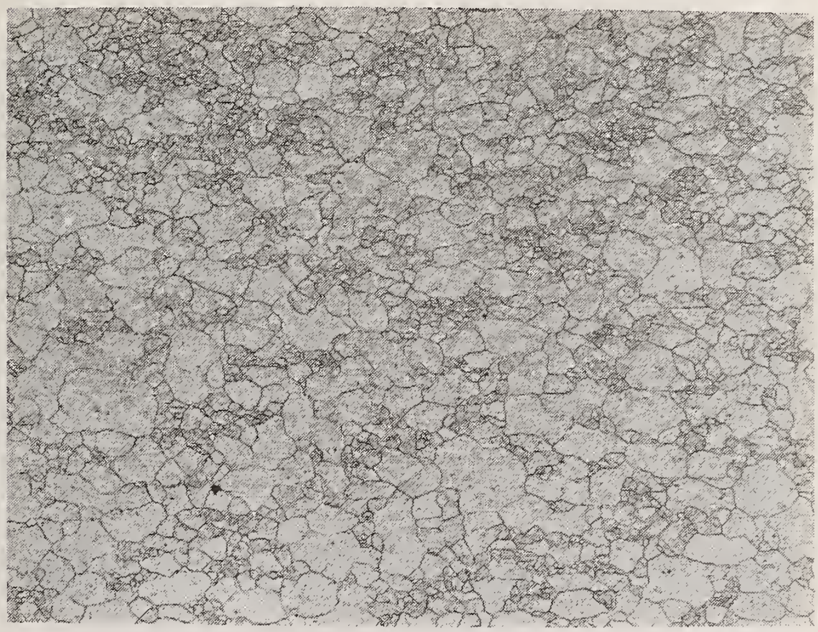

Figure A-9. Microstructure of transverse section through member B near fracture. Etch: 10% sodium hydroxide. X 100

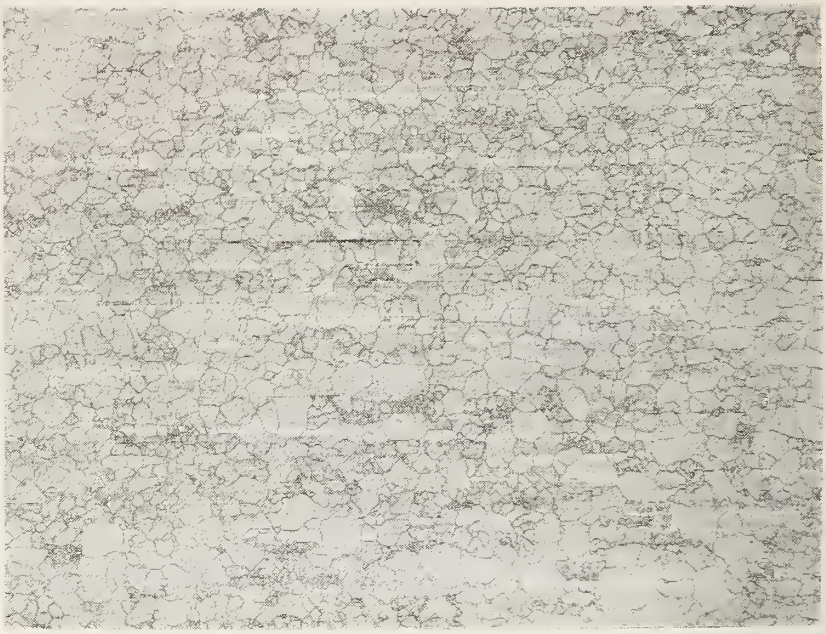

Figure A-10. Longitudinal section through member A. Etch: 10% sodium hydroxide. X 40

Figure A-11. Longitudinal section through member B. Etch: 10% sodium hydroxide. X 40

A.6. Tensile Tests

Two tensile specimens were taken from the top right rail of the bed section. They were machined according to ASTM Specification E8 for subsize specimens. The specimens were pulled at a rate of 0.02 inch per minute. The results, to the nearest 25 psi, are as follows:

Specimen	Ultimate tensile strength (psi)	Yield strength 0.2% offset (psi)	Elongation, % in 1 inch
I	37,750	31,575	12.5
II	37,375	31,400	14.1

The 1970-1971 edition of Aluminum Standards and Data [11] published by the Aluminum Association specifies the following minimum properties for aluminum alloy 6061 in the T6 temper:

Ultimate tensile strength	38,000 psi
Yield strength, 0.2% offset	35,000 psi
Elongation, percent in 2 inches	8%

With respect to the above specification the results from the tensile tests indicate that the ultimate tensile strength is slightly lower than acceptable, and that the yield strength is about 3,500 psi below the minimum acceptable. Because of differences in gauge length between the specification and specimens, elongation is not directly comparable. However, the ultimate tensile strength does meet the specified minimum of 35,000 psi listed in NFPA 193 [2].

A.7. Summary

The ladder was being used within the load-carrying limits specified in NFPA 193 (par 132). Of those parts examined only members B, C, and D (top left rail, bed section; lower right rail, bed section; lower right cap, fly section, respectively) were hard enough to be in the T6 temper. The T6 temper is obtained by artificial aging at about 350°F for 7-9 hours after a solution treatment. T-members A and E were softer than acceptable for the T6 temper; the hardness values are in the range of the T4 temper which is produced by naturally aging at room temperature. Tensile tests on material from member A, however, indicate that the ultimate and yield strengths are lower than acceptable for aluminum alloy 6061-T6, and higher than would normally be expected for 6061-T4.

Three areas of member A covering a span of about ten feet were examined and all were soft. If this member had been softened by exposure to fire, it seems very unlikely that this length of material would have been affected while the other T-member on the same side of the ladder was unaffected.

While only one area of member E was examined, it was much softer than the corresponding area of the other T-member on the same side of the ladder. This condition indicates that the soft members were probably improperly heat treated initially rather than softened in a fire.

The cracks that appear on the edges of some of the members most likely occurred during the extrusion process. Although some of the fractures went through these cracks, they do not appear to have originated at the cracks. The fractures appear to have been caused by overload.

The microstructure of the material examined appears quite satisfactory.

APPENDIX B. LADDER FAILURE B

The upper two sections of a failed 35 foot, three section, aluminum alloy extension ladder used for fire fighting purposes were submitted to Mr. T. Robert Shives of the Mechanical Properties Section, Metallurgy Division of the National Bureau of Standards for examination. The ladder was reported to have been fabricated from aluminum alloy 6061 in the T6 temper.

According to information furnished by the fire department, the ladder had failed during a training exercise. At the time of failure, the ladder was extended to its full length and was leaning against a building. Two men were on the ladder; one was at the top preparing to step onto the roof of the building, and the second had just stepped onto the middle fly section when there was a loud cracking sound and the ladder began collapsing toward the building. The ladder buckled and fell to the left.

B.1. Visual Examination

The two sections of the ladder submitted for examination are shown as received in figure B-1. The letter designations on the photograph indicate the approximate locations in the rail members where hardness and thickness measurements were made and where tensile specimens were taken. The "A" rails were on the right side of the ladder and the "B" rails were on the left side. Locations 1, 2, and 3 were in the middle fly section and locations 4, 5, F, and 6 were in the top section. Each rail member of the ladder was comprised of two extrusions riveted together as shown in figure B-2. The two extrusions in each rail were designated as inside and outside, respectively, according to their location in the ladder.

When the ladder failed, the top section buckled just above the top of the middle fly section. None of the four extruded members in the top section fractured completely, but all exhibited cracks or tears and considerable deformation as shown in figures B-3, B-4 and B-5. Much of the cracking was longitudinal (parallel to the extrusion direction and to the length of the ladder) and occurred at the 90° angles in the transverse cross section of the extruded members and at rivet holes. When the ladder buckled, the sizes of these angles changed in the region of deformation, in some cases increasing to nearly 180°.

There was no visual evidence such as soot to indicate that the ladder had been exposed to fire.

B.2. Fractographic Examination

Several of the partially fractured surfaces were examined optically, and one such surface was examined with the scanning electron microscope. Figure B-6 is a scanning electron photomicrograph showing the entire width of the fracture surface. Note that the left and right sides of the fracture as shown in the figure have distinctly different features. Figure B-7 shows part of the left side of the fracture at a higher magnification. The features indicate that a ductile, overload fracture occurred. The right side of the fracture as it appears in figure B-8 seems to have been badly smeared. This side was on the compression side of the fracture and the smearing apparently was caused by the opposing sides of the fracture moving one over the other. This crack, and the others examined, appear to have been produced by a single event when the ladder failed. Therefore, the cracks appear to have occurred as a result of failure, rather than having contributed to it.

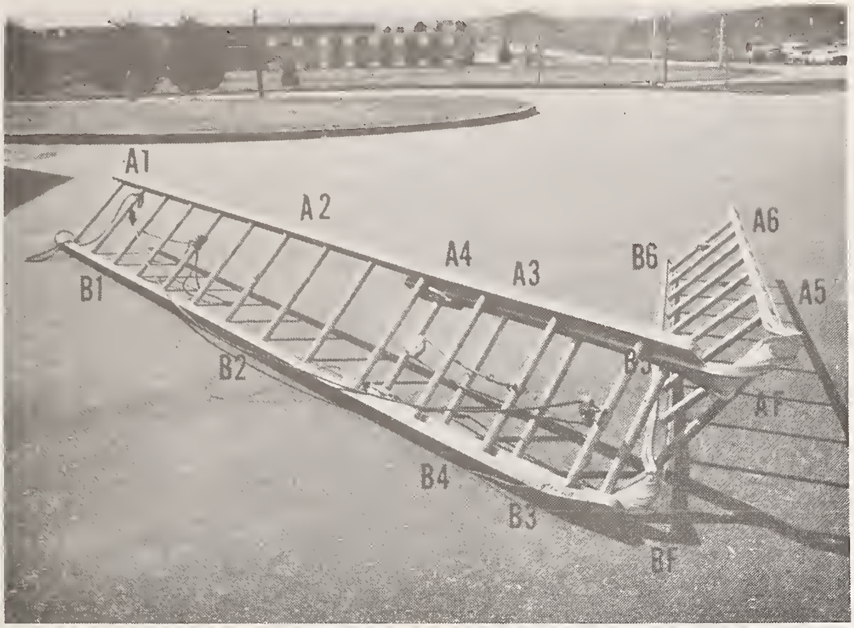

Figure B-1. Failed fire ladder as received. The number and letter designations indicate locations of the ladder rails which were examined. The "A" rails are on the right side and the "B" rails are on the left side.

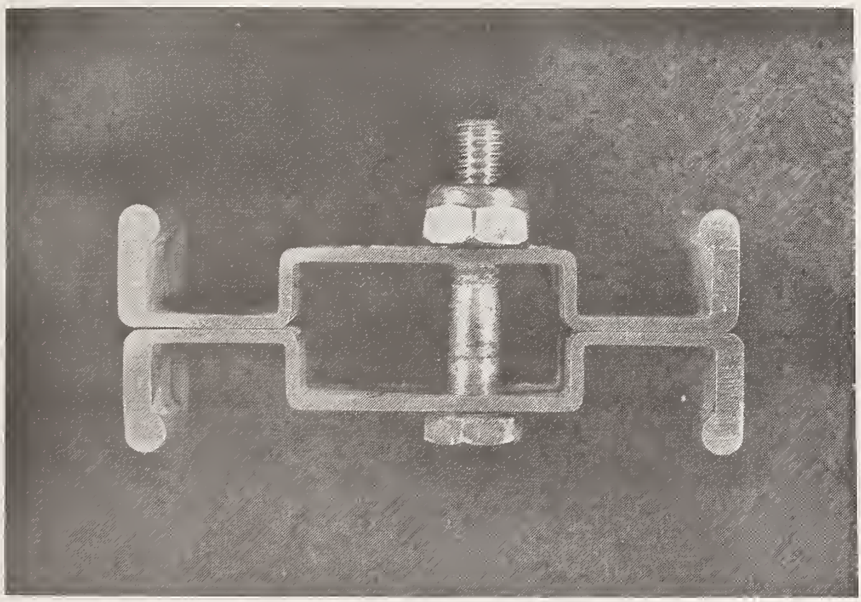

Figure B-2. Cross section through one of the ladder rails showing the two extruded parts. These parts were riveted together. The bolt shown in the photograph was used to attach a fitting to the ladder. X 1

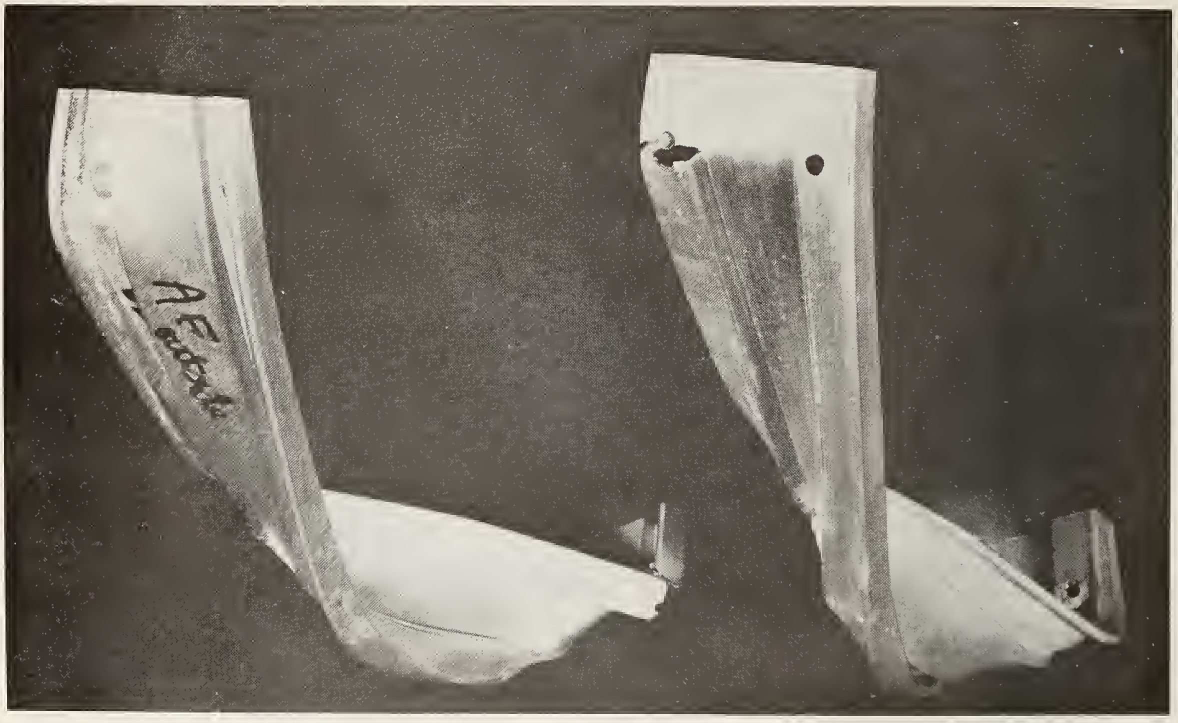

Figure B-3. Parts of the deformed extruded members from location AF. AF outside is at the left and AF inside is at the right. X 1/3

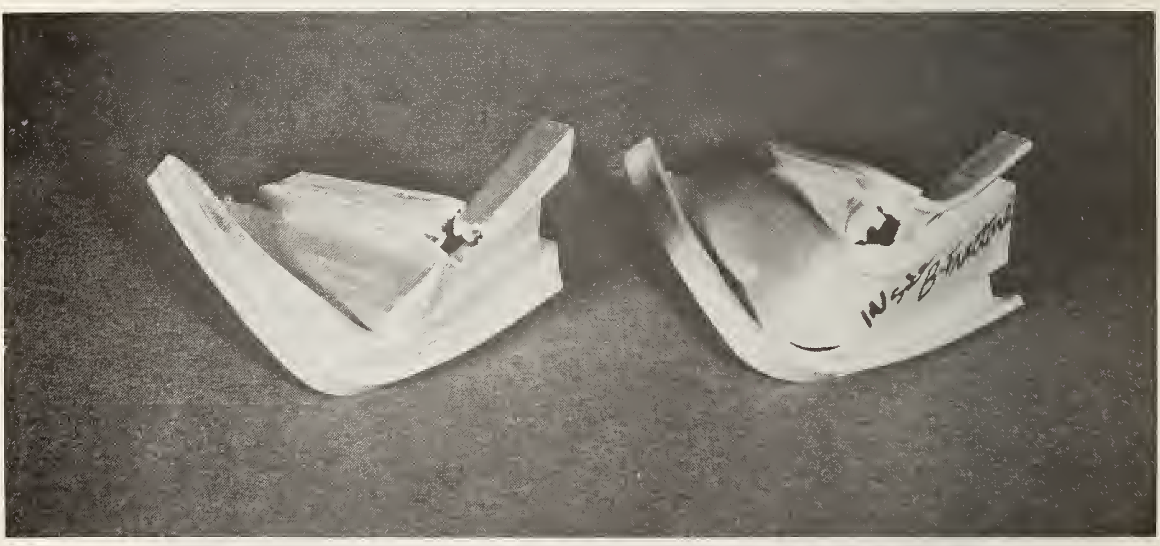

Figure B-4. Parts of the deformed extruded members from location BF. BF outside is at the left and BF inside is at the right. X 1/3

Figure B-5. Deformed part of extruded member B outside from location BF (shown on the right in figure 4). The hole in the center at the top is where a rivet had pulled out. Some cracks can be seen. X 1

Figure B-6. Scanning electron photomicrograph showing the fracture surface of a crack at location BF inside. The features at the left indicate ductile overload. The features on the right indicate smearing on the compression side of the fracture. X 24

Figure B-7. Scanning electron photomicrograph of fracture at location BF inside showing ductile overload (left side of figure 6). X 240

Figure B-8. Scanning electron photomicrograph of fracture at location BF inside showing smearing on the compression side of the fracture. X 235

B.3. Hardness Measurements

Rockwell 45T hardness measurements were made on each of the extruded rail members at the locations indicated in figure B-1. Five measurements were made at each location. The results of these measurements and the approximate Rockwell B equivalent hardness numbers are given in table B-1. Because of the considerable spread in the results, the hardness data are reported as ranges. The acceptable range of Rockwell B hardness for aluminum alloy 6061 in the T6 temper is 47-72 [10]. The hardness was below the acceptable minimum for at least one location in each of the eight extruded members, and many of the results that fell within the acceptable range were near the lower limit.

Table B-1. Results of Hardness Measurements

Location	Rockwell 45T Hardness	Approximate Rockwell B Equivalent
A1 inside	32.5-37.0	51-57
A2 inside	29.0-33.0	46-52
A3 inside	26.5-29.5	43-47
A4 inside	18.0-20.0	32-34
AF inside	21.0-22.0	36-37
A5 inside	27.0-28.5	44-46
A6 inside	22.5-24.0	38-40
A1 outside	28.5-30.0	46-48
A2 outside	27.0-32.0	44-50
A3 outside	21.0-23.5	36-39
A4 outside	21.0-24.5	36-40
AF outside	20.0-24.0	34-40
A5 outside	21.5-24.5	36-40
A6 outside	24.0-28.0	40-45
B1 inside	16.0-20.0	30-34
B2 inside	12.0-14.0	23-26
B3 inside	13.0-17.0	24-31
B4 inside	21.0-24.0	36-40
BF inside	22.5-23.5	38-39
B5 inside	31.0-32.0	49-50
B6 inside	30.0-31.0	48-49
B1 outside	27.5-30.0	44-48
B2 outside	28.5-30.5	46-48
B3 outside	27.5-30.5	44-48
B4 outside	29.0-31.0	46-49
BF outside	27.5-30.0	42-48
B5 outside	29.0-30.0	46-48
B6 outside	26.5-28.5	43-46

B.4. Tensile Properties

Tensile specimens were machine from several of the locations indicated in figure B-1 in accordance with ASTM Standard E8-68. The specimens were pulled at a cross head rate of 0.04 inches per minute. Ultimate tensile strength, 0.2% offset yield strength, and, for those specimens which failed within the gauge length, percent elongation are reported in table B-2. The specified minimum values [11] for mechanical properites for aluminum alloy 6061 in the T6 temper are as follows:

Ultimate tensile strength	38.0 ksi
Yield strength, 0.2% offset	35.0 ksi
Elongation, percent in two inches	8%

One of the 16 tensile specimens had an ultimate tensile strength lower than the specified minimum, and the results from several others were close to the specified minimum. The yield strength of six of the 16 specimens was below the specified minimum. Elongation for all specimens for which it could be determined met specifications.

Table B-2. Results of Tensile Tests

Specimen Location	Ultimate Tensile[a] Strength, ksi	Yield Strength,[a] 0.2% Offset, ksi	Percent Elongation[b] in 2 inches
A1 inside	45.5	42.0	10.2
A3 inside	40.7	36.6	9.7
A4 inside	38.8	32.1	c
A5 inside	38.2	31.7	c
A1 outside	41.2	37.7	11.0
A3 outside	38.6	34.7	9.9
A4 outside	43.8	38.3	c
A5 outside	40.4	34.2	10.4
B1 inside	38.6	31.6	c
B3 inside	37.5	30.1	11.1
B4 inside	41.4	36.0	c
B5 inside	38.1	35.3	10.2
B1 outside	43.6	39.5	11.2
B3 outside	43.2	38.2	10.9
B4 outside	42.3	38.1	11.5
B5 outside	42.9	38.8	12.0

[a]Given to the nearest 0.1 ksi.
[b]Given to the nearest 0.1 percent.
[c]Specimen broke outside gauge length.

B.5. Thickness Measurements

Thickness measurements were made on the tensile specimens. The results of these measurements are given in table B-3. The variation in thickness within any given extruded member was small, but the maximum thickness measured was about 20% greater than the minimum thickness measured.

Table B-3. Results of Thickness Measurements

Location	Thickness (in)
A1 inside	0.0723
A3 inside	0.0721
A4 inside	0.0611
A5 inside	0.0605
A1 outside	0.0718
A3 outside	0.0714
A4 outside	0.0618
A5 outside	0.0616
B1 inside	0.0620
B3 inside	0.0616
B4 inside	0.0618
B5 inside	0.0617
B1 outside	0.0610
B3 outside	0.0612
B4 outside	0.0609
B5 outside	0.0609

Unetched cross sections taken from both the region of buckling and away from it for four different extruded members were examined metallographically. The microstructure of the material appeared to be essentially the same in all cases. It was clean with a relatively uniform distribution of precipitate. Figure B-9 shows a typical unetched cross section.

Etched specimens taken from various locations in the ladder revealed wide variations in grain size and grain elongation, ranging from what appears to be an "as extruded" microstructure at location B3 (figure B-10) to what appears to be a nearly completely recrystallized microstructure as found at location BF (figure B-11). This location was selected to show the tip of a longitudinal crack at one of the 90° angles of the extrusion in the region of buckling. The crack appears to be intergranular. The microstructure in an area at location BF slightly removed from that shown in figure B-11 (figure B-12) exhibits more of the larger precipitate particles than that shown in figure B-11 and what appears to be an extrusion lap or seam. Etched microstructures in two other areas are shown in figures B-13 and B-14. In area A1 (figure B-13), the grains were relatively fine and nearly equiaxed in a band along each surface. Outside these bands (toward the interior of the cross section) the grains are elongated in the longitudinal direction of the extrusion. Another extrusion lap or seam can be seen. The microstructure in a longitudinal cross section at location AF is shown in figure B-14. There are no bands of fine, equiaxed grains near the surface, but there are some very fine grains near the center. It appears as though recrystallization had begun to take place, but was far from being complete.

Figure B-9. Photomicrograph of a typical unetched cross section (longitudinal) showing precipitate particles. This cross section is from location BF inside. X 60

Figure B-10 . Microstructure of longitudinal cross section from location B3 inside. Grains are elongated in the longitudinal direction of the ladder. The microstructure appears to be in the "as extruded" condition. Etch: 10% NaOH. X 60

Figure B-11. Microstructure of transverse cross section from location BF inside. The microstructure appears to be nearly completely recrystallized. There is an intergranular longitudinal crack. Etch: 10% NaOH. X 60

Figure B-12. Microstructure of longitudinal cross section from location BF inside. An extrusion lap or seam is exhibited (running vertically) in the figure. Etch: 10% NaOH. X 60

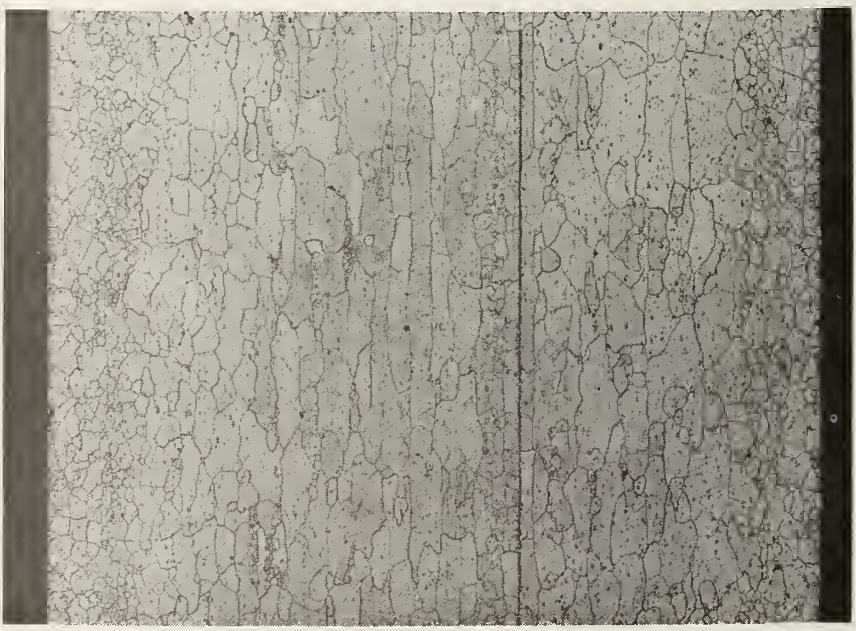

Figure B-13. Microstructure of longitudinal cross section from location Al inside. There are fine grains near the surfaces and elongated grains in the center. An extrusion lap or seam can be seen. Etch: 10% NaOH. X 60

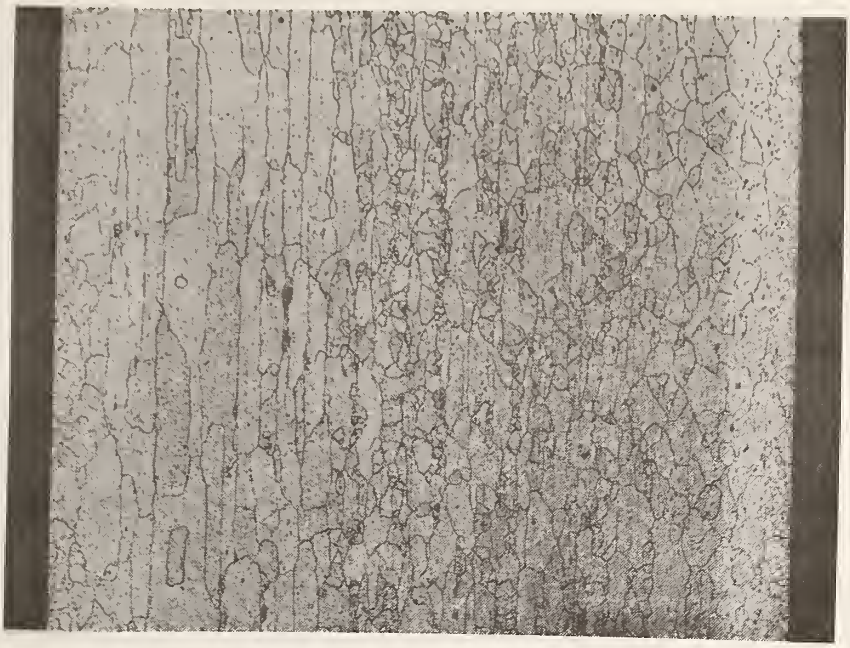

Figure B-14. Microstructure of longitudinal cross section from location AF showing fine grains near the center. There appears to have been incomplete recrystallization and there is considerable fine precipitate. Etch: 10% NaOH. X 60

B.7. Discussion

The results of both the tensile tests and the hardness measurements indicate that certain parts of the extruded rail members of this fire fighting ladder were not in the T6 temper as specified. This coupled with a lack of evidence that the ladder had been exposed to fire indicates that at least parts of some of the extruded members had not been properly heat treated, if, indeed, they had been heat treated at all.

The grains elongated in the longitudinal direction in some areas (as shown in figure B-10) provide further evidence that either no heat treatment or an improper heat treatment was given to some of the material. Material from the location where figure B-10 was taken had low hardness, low ultimate tensile strength, and low yield strength compared to other areas examined. The best mechanical properties were found in material which appears to have a partially recrystallized microstructure. Thus, material which shows evidence of having been heat treated exhibited better mechanical properties than the material which appeared to be "as extruded".

There was a considerable variation in thickness among the various extruded members. The thickest specimen measured was about 20% greater in thickness than the thinnest specimen measured.

The buckling of the ladder occurred where the strength of the material was low, although not the lowest found in the extruded members. The extruded members which buckled were among the thinner members, although not the thinnest. A stress analysis would be necessary to determine the point at which the load concentration was greatest, but apparently a combination of low strength material, thin members, and high load concentration caused the ladder to fail where it did.

The cracks found in the extruded members appear to have occurred at the time of failure, and therefore probably did not contribute to the failure. Extrusion laps or seams found in two of the areas examined, while considered undesirable, apparently did not contribute to the failure.

B.8. Conclusions

1. This fire fighting ladder appears to have failed where it did due to a combination of low strength materials, thin members, and a probable high load concentration.

2. There was no evidence that the ladder had been exposed to fire or excessive heat.

3. No evidence was found that any cracks were present before the ladder failed, although some cracks did form as the ladder buckled.

4. The mechanical properties varied considerably among the locations examined.

5. The results of both hardness measurements and tensile tests indicated that, in some regions, the mechanical properties of the extruded members did not meet the minimum hardness and strength requirements for aluminum alloy 6061 in the T6 temper.

6. In many areas where the mechanical properties did meet the minimum specified values, they were close to the minimum.

7. Examination of the microstructures indicated that some parts of the extruded members may have been in the "as extruded" condition, and therefore were never properly heat treated, and that other parts were improperly heat treated.

8. There was an apparent correlation between the "as extruded" microstructure and poor mechanical properties.

9. Extrusion seams or laps were found in two areas examined, but they apparently did not contribute to the failure.

10. Thickness measurements indicated that some of the extruded members were about 20% thicker than the thinnest members.

In summary, the most deleterious condition found in the ladder rail material was the lack of a proper heat treatment which resulted in mechanical properties which do not meet specifications.

The uppermost section from an aluminum fire extension ladder had failed in service when subjected to a fire. According to the information provided, this 28-foot aluminum ladder, extended to a length of about 26 feet, was placed at an angle of about 80 degrees into a window of the fully-involved third floor of a three-story apartment building. The third floor suddenly gave way, blowing out the second-floor window below that in which the ladder had been placed. As the second floor was now also fully involved, the ladder was reportedly exposed to direct flame contact for approximately 20 seconds before it was pulled away from the building. No one was on the ladder at the time of the incident although a fireman was about to climb it. The failed ladder was submitted for examination to Mr. T. Robert Shives, Metallurgist in the Mechanical Properties Section, Metallurgy Division of the National Bureau of Standards.

The ladder was bent and twisted from about the third to the eighth rung, counting from the top. The fifth, sixth, and seventh rungs from the top had fractured and sections were missing. A black, sooty material covered the ladder from the eighth rung from the top to the top. The deformed section of the ladder is shown in figures C-1 and C-2. The specified material for the ladder is aluminum alloy 6061-T6 (an age hardening alloy).

Sections of the side rails and rungs from damaged and undamaged areas were selected for hardness measurements and macroscopic and microscopic examinations. In addition, a stock piece of 6061-T6 was examined for comparison.

C.1. Hardness Measurements

Hardness measurements were made on the Rockwell 30T scale. The R_{30T} scale was used instead of the Rockwell B scale because, for the softer specimens, there was an insufficient thickness of material to support the load (100 kg) employed when using the R_B scale and some of the results on the softer material were not within the range covered by the R_B scale. R_{30T} hardness values and the approximate Rockwell B equivalent values are given below:

Part and Location	R_{30T}	Approx R_B equiv
Rail		
Near bottom undamaged	58	54
Near top, slightly blackened but not deformed	56	48
Blackened but not deformed (between 4th and 5th rung)	48	30
Twisted and blackened	37	6
Rung		
Undamaged(#12 from top)	53	42
Damaged(#7 from top)	29	off scale
Control piece 6061-T6	57	52

The acceptable R_B hardness range for aluminum alloy 6061-T6 is 47-72 [10]. The sections of undamaged-unblackened side rail, undeformed-blackened side rail near the ladder top, and undamaged rung that were examined exhibited hardness values within the acceptable range. The rail section in the area which was not deformed, but was near the deformed area had softened considerably. Sections from the twisted rail and the damaged rung had softened considerably more than the undeformed rail near the twisted section, but were still much harder than they would have been in the annealed condition. Aluminum 6061 in the annealed condition (6061-0) would have a Rockwell B hardness approaching zero.

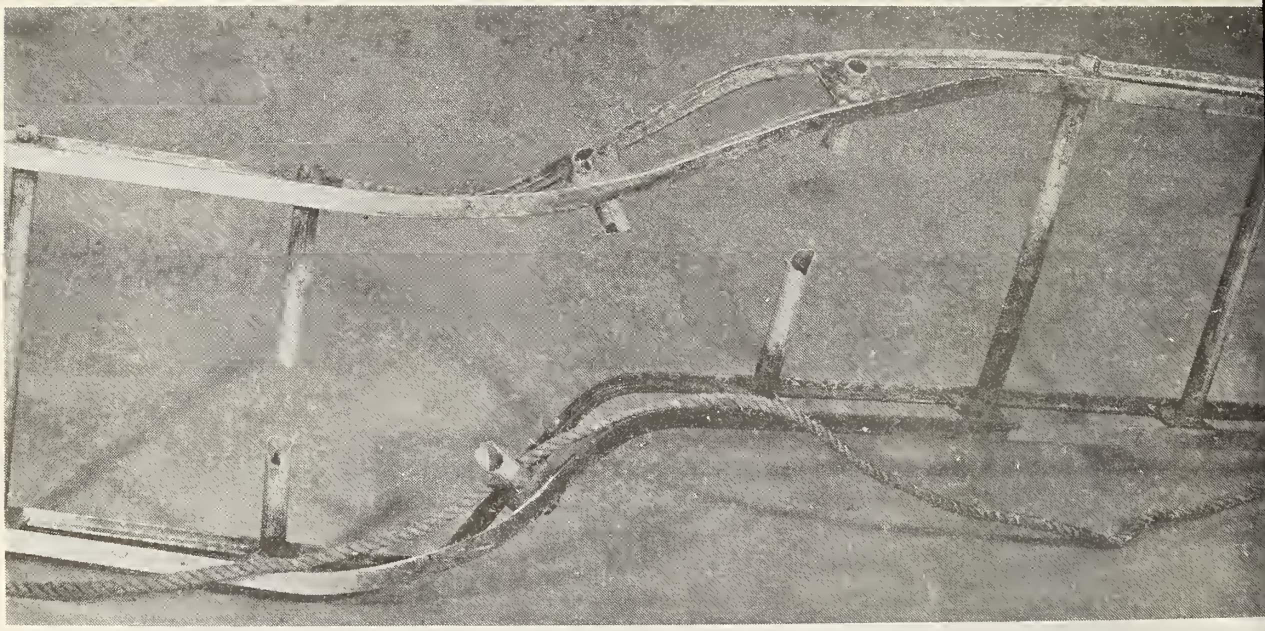

Figure C-1. Fire ladder as received showing damaged area at right. X 1/10

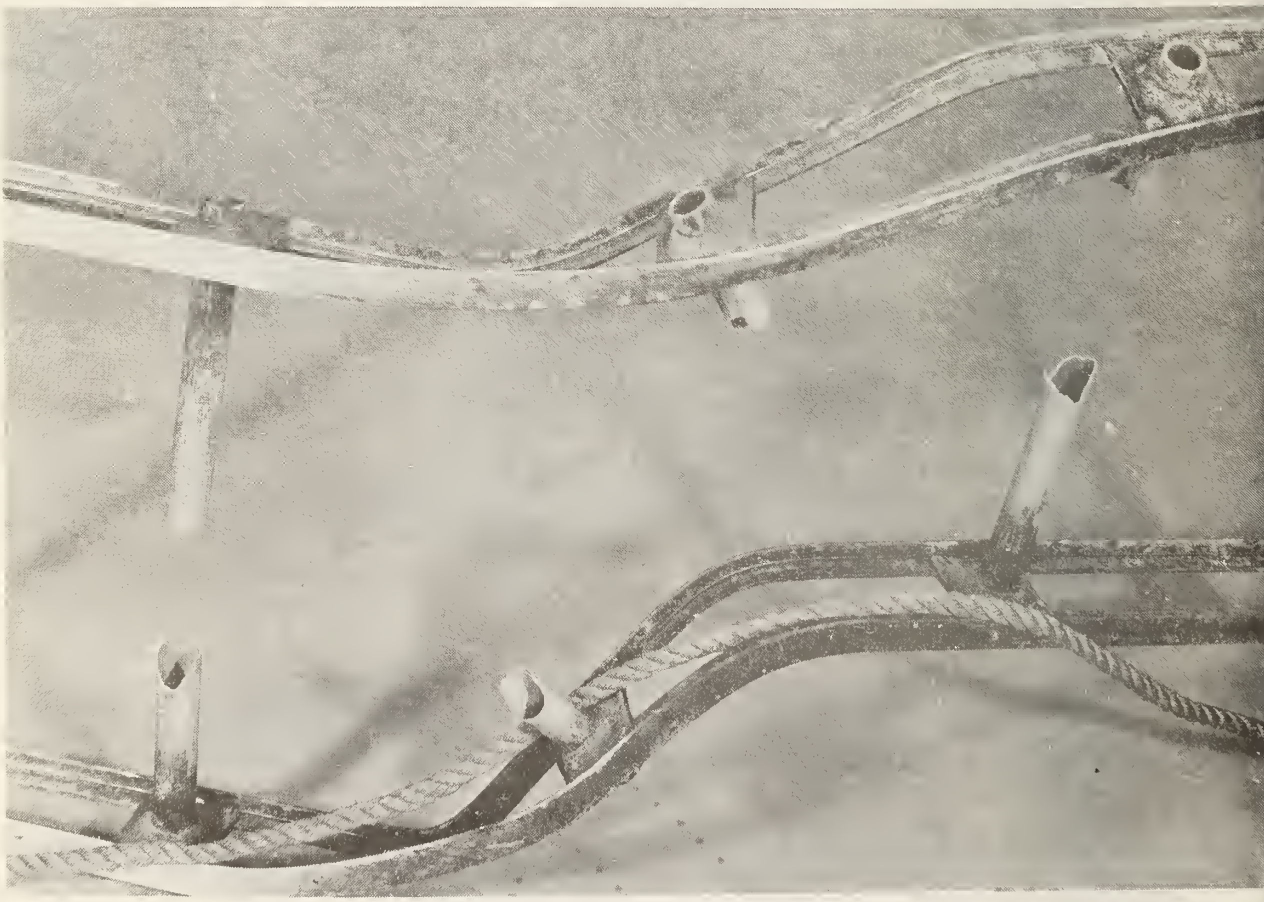

Figure C-2. Damaged portion of ladder as received. X 1/5

C.2. Macroscopic Examination

Three sections of rail were examined macroscopically as shown in figure C-3. The unaffected area near the bottom of the ladder (figure C-3a) exhibits flow lines caused by the extrusion process and shows no evidence of having been overheated. A blackened but undeformed section near the top of the ladder, which had shown only a slightly reduced hardness compared to the bottom, exhibits a structure which had been affected by heat (figure C-3b). The material had apparently recrystallized. The section shown in figure C-3c is from the deformed part of the ladder. The material had recrystallized with some subsequent grain growth.

C.3. Microscopic Examination

A metallographic examination of side rail material indicates that the precipitate particles increase in size going from (1) the undamaged area to (2) the blackened but undeformed area to (3) the twisted area (figures C-4, C-6, and C-8, respectively). This is expected, based on the hardness measurements. The larger precipitate particle size in the areas subjected to heat indicates overaging of the material.

The grain size of material from both undamaged and deformed areas was essentially the same (figures C-5 and C-9, respectively). The grain size of material from the blackened but undeformed area (figure C-7) of the ladder was somewhat finer than that shown in figures C-5 and C-9. Recrystallization has apparently taken place in the heated areas, as was indicated by the macroetched specimens.

The microstructure of the rung material (figures C-10 to C-13) indicates an increase in grain size in the damaged material (figure C-13) compared to the undamaged material (figure C-11). Unetched specimens (figures C-10 and C-12) exhibited very little difference in the precipitate particles between the two conditions.

For comparison, the microstructure of a stock piece of 6061-T6 is shown in figures C-14 and C-15.

The material adjacent to the fracture of rung #5 (counting from the top) was also examined metallographically. Two sections through the fracture were selected for examination. The grain size did not appear to be significantly different from that shown in figure C-13 (microstructure of damaged rung). The fracture was definitely intergranular. There appeared to have been fusion in the vicinity of the grain boundaries adjacent to the fracture. The grains protruding at the fracture reached a high enough temperature so that there was apparent surface melting of the exposed parts of the grains. The surface tension of this melted portion of the grains caused rounding of the grains.

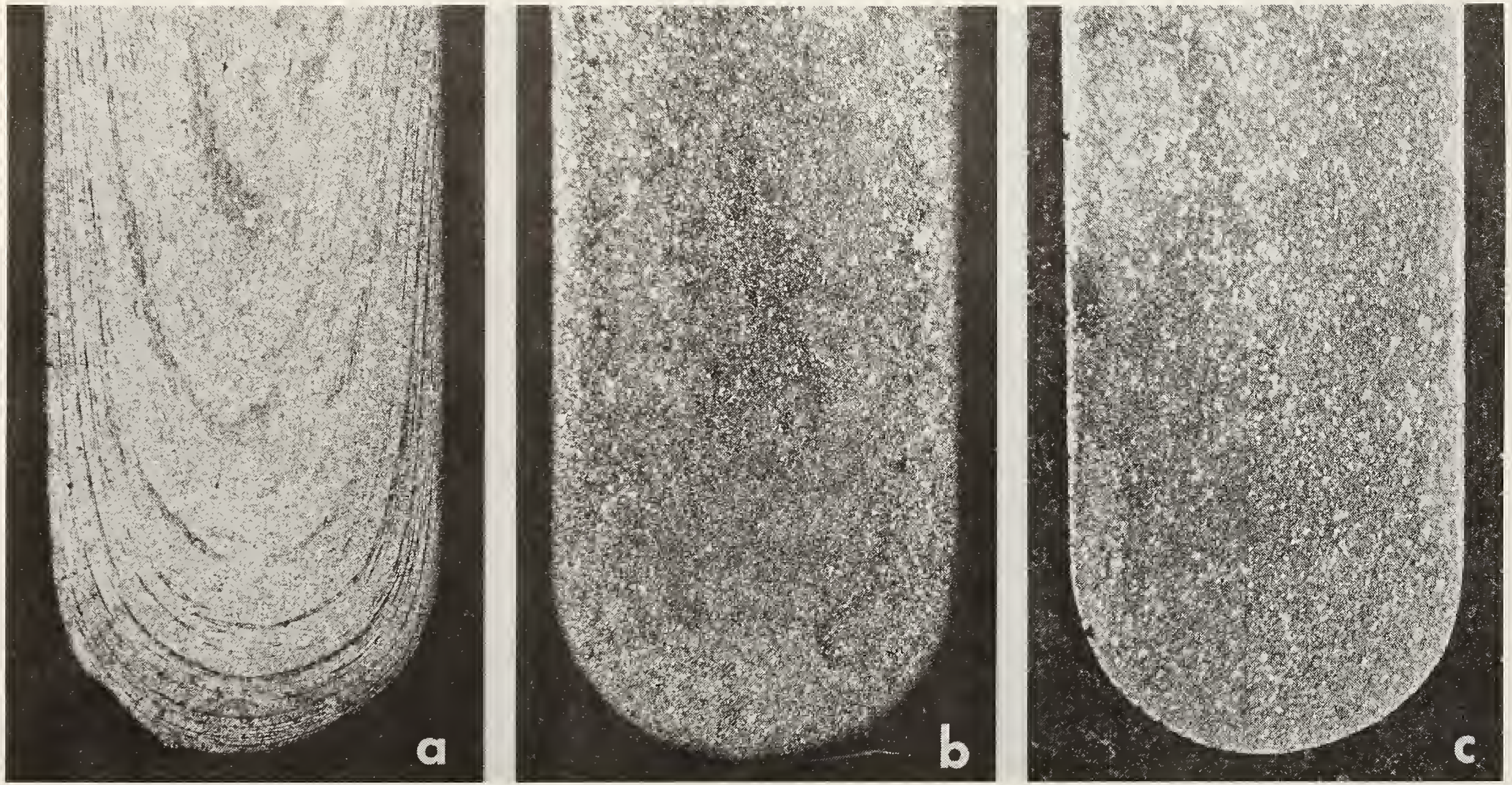

Figure C-3. Macroetched sections of ladder side rail. X 11
Etch: Solution containing 2.5 cc HCl, 3.5 cc HNO_3, 1.0 cc H_2SO_4, 2.0 cc HF, 125 cc H_2O.

a. Section near bottom unaffected by heat.
b. Blackened, but undeformed section near top.
c. Section from twisted area.

Figure C-4. Section of unaffected rail. Unetched. X 200

Figure C-5. Microstructure of unaffected rail. Etch: 10% NaOH. X 200

Figure C-6. Section of rail from blackened, but undeformed area. Unetched. X 200

Figure C-7. Microstructure of blackened, but undeformed section of rail. Etch: 10% NaOH. X 200

Figure C-8. Section of rail from twisted area. Unetched. X 200

Figure C-9. Microstructure of section of rail from twisted area. Etch: 10% NaOH. X 200

Figure C-10. Section of rung unaffected by heat. Unetched. X 200

Figure C-11. Microstructure of rung unaffected by heat. Etch: 10% NaOH. X 200

Figure C-12. Section from damaged rung. Unetched. X 200

Figure C-13 . Microstructure of damaged rung. Etch: 10% NaOH. X 200

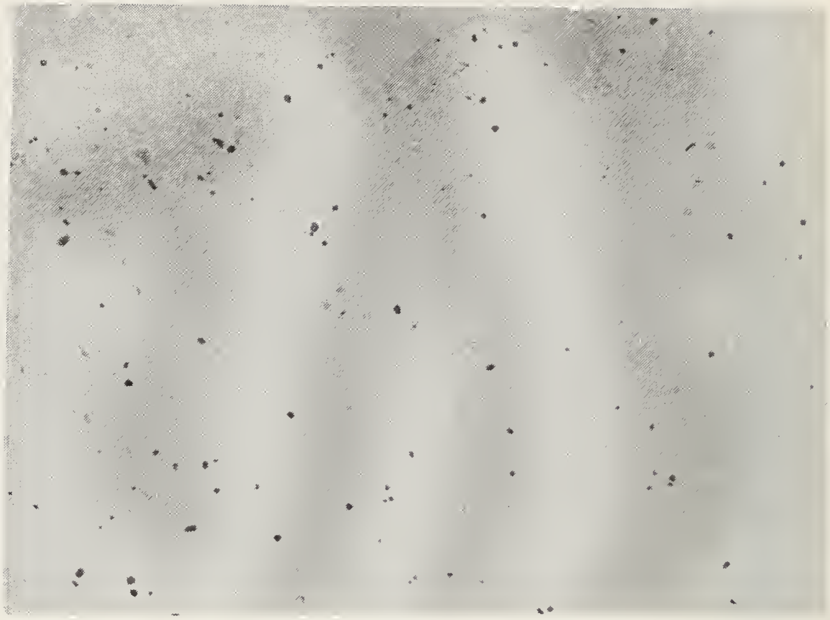

Figure C-14. Stock 6061-T6. Unetched. X 200

Figure C-15. Microstructure of stock 6061-T6.
Etch: 10% NaOH. X 200

C.4. Temperature of Failure

In order to estimate the temperature to which the ladder was subjected at failure, a number of one-half inch thick rail sections were cut from the ladder and heated at selected temperatures in an air furnace with the air being circulated by a fan. After the furnace treatment, the sections were cooled in still air. Hardness measurements (R_{30T}) were then made.

Data for Heat Treated Rail Sections

Temperature (°F)	Time (min)	R_{30T}	Approx R_B equiv
400	1	58	54
500	1	58	54
600	1	58	54
700	1	58	54
800	1	54	44
900	1	54	44
1000	1	47	28
1100	1	38	8
1200	1	38	8
1300	1	12	off scale
400	2 1/2	56	48
500	2 1/2	57	52
600	2 1/2	56	48
700	2 1/2	55	46
800	2 1/2	48	30
900	2 1/2	41	14
1000	2 1/2	20	off scale
1100	2 1/2	4	off scale

It was stated by witnesses that the ladder had been subjected to the fire for a very short time. That is the reason for the short duration of the above tests.

It is not known how closely our tests approximated the actual conditions leading to failure. Small sections were used in our tests rather than the complete ladder itself, the cooler parts of which would have acted as a heat sink during the fire. With these qualifications in mind, rough estimates of temperatures to which the ladder was subjected are as follows:

1 minute exposure	1100-1200°F
2 1/2 minute exposure	850- 950°F

C.5. Fasteners

The fasteners in this ladder appear to have been made of an aluminum alloy and not of plated steel.

C.6. Summary

The ladder appears to have been made of properly heat treated aluminum alloy 6061-T6. There is no evidence that the lower, unblackened part of the ladder had been overheated either in prior service or at the time of failure. The damaged material appears to have been severely overaged, but not annealed, during the fire. The fasteners appear to have been made of an aluminum alloy and not of steel. A rough estimate of the temperature to which the ladder was subjected is as follows, depending on length of exposure to the heat:

1 minute exposure	1100-1200°F
2 1/2 minute exposure	850- 950°F

APPENDIX D. CORRELATION OF TENSILE AND YIELD STRENGTHS WITH HARDNESS FOR ALUMINUM ALLOY 6061-T6

A newly purchased 35-foot, 2-section fire department ground ladder was cut into sections for the purpose of obtaining hardness specimens. Specimens were taken from each rail member at the 3rd, 9th and 17th segment from the bottom of both the bed and fly sections. The specimens were identified as follows:

Segment from bottom	Bed Section (Specimen No.)			
	Top right	Bottom right	Top left	Bottom left
3	1	4	7	10
9	2	5	8	11
17	3	6	9	12

Segment from bottom	Fly Section (Specimen No.)			
	Top right	Bottom right	Top left	Bottom left
3	13	16	19	22
9	14	17	20	23
17	15	18	21	24

Specimens were machined according to ASTM Specification E8 for standard specimens. Hardness measurements taken on the specimens gave the following results:

Specimen	R_B	Specimen	R_B	Specimen	R_B
1	52.7	9	52.0	17	54.8
2	53.9	10	51.3	18	54.3
3	56.6	11	52.6	19	56.3
4	57.2	12	52.8	20	56.2
5	56.1	13	55.2	21	54.4
6	54.4	14	55.1	22	55.0
7	57.2	15	54.5	23	55.0
8	53.2	16	54.4	24	54.5

Each hardness value is the average of 6 determinations. All of the above values are well within the acceptable hardness range for 6061-T6.

In order to produce a range of hardness values and mechanical properties, specimens 5 through 24 were overaged in an air furnace and air cooled prior to tensile tests. Specimens given more than one heat treatment were cooled to room temperature between treatments. Heat treatments are given below:

Specimens	5 - 8:	30 min at 425°F + 30 min at 450°F 30 min at 500°F
	9 -12:	15 min at 550°F
	13 -16:	25 min at 550°F + 10 min at 575°F
	17 -20:	four separate 5 min treatments at 575°F
	21 -24:	30 min at 525°F + 30 min at 525°F

All specimens were tested on the tensile testing machine at a rate of 0.02 inch per minute. The results of the tensile tests and the hardness measurements are given below. Ultimate tensile strength and yield strength are given to the nearest 25 psi. Each hardness value is the average of six measurements.

Table D-1. Results of Hardness, Tensile Strength, and Yield Strength Measurements on 6061-T6 Aluminum Specimen

Specimen	Hardness R_B	Ultimate tensile strength (psi)	Yield strength 0.2% offset (psi)	Elongation in 2 inches (%)
1	52.7	43,300	40,025	8.0
2	53.9	44,000	40,600	8.1
3	56.6	44,600	41,050	7.8
4	57.2	44,900	41,075	8.8
5	41.9	38,450	34,550	9.5
6	39.2	38.100	33,825	9.8
7	42.4	38,675	34,800	9.0
8	38.1	37,100	32,600	8.1
9	26.2	34,375	28,575	10.4
10	25.5	34,250	28,000	11.0
11	26.8	34,600	28,950	10.5
12	21.4	34,075	28,350	10.0
13	9.9	31,800	25,250	10.7
14	5.3	30,700	23,525	10.3
15	8.7	31,325	23,825	11.0
16	8.7	31,375	24,150	11.1
17	18.3	32,800	26,425	10.4
18	15.3	32,350	25,750	10.7
19	18.4	33,150	26,725	9.0
20	17.2	32,775	26,300	10.6
21	26.1	34,600	28,850	8.6
22	26.0	34,525	28,775	9.9
23	22.9	34,800	28,950	10.6
24	28.6	35,050	29,625	9.5

The above data are plotted in figure D-1. This figure may be used to convert hardness measurements made on 6061-T6 aluminum alloys to the corresponding tensile strength and yield strength.

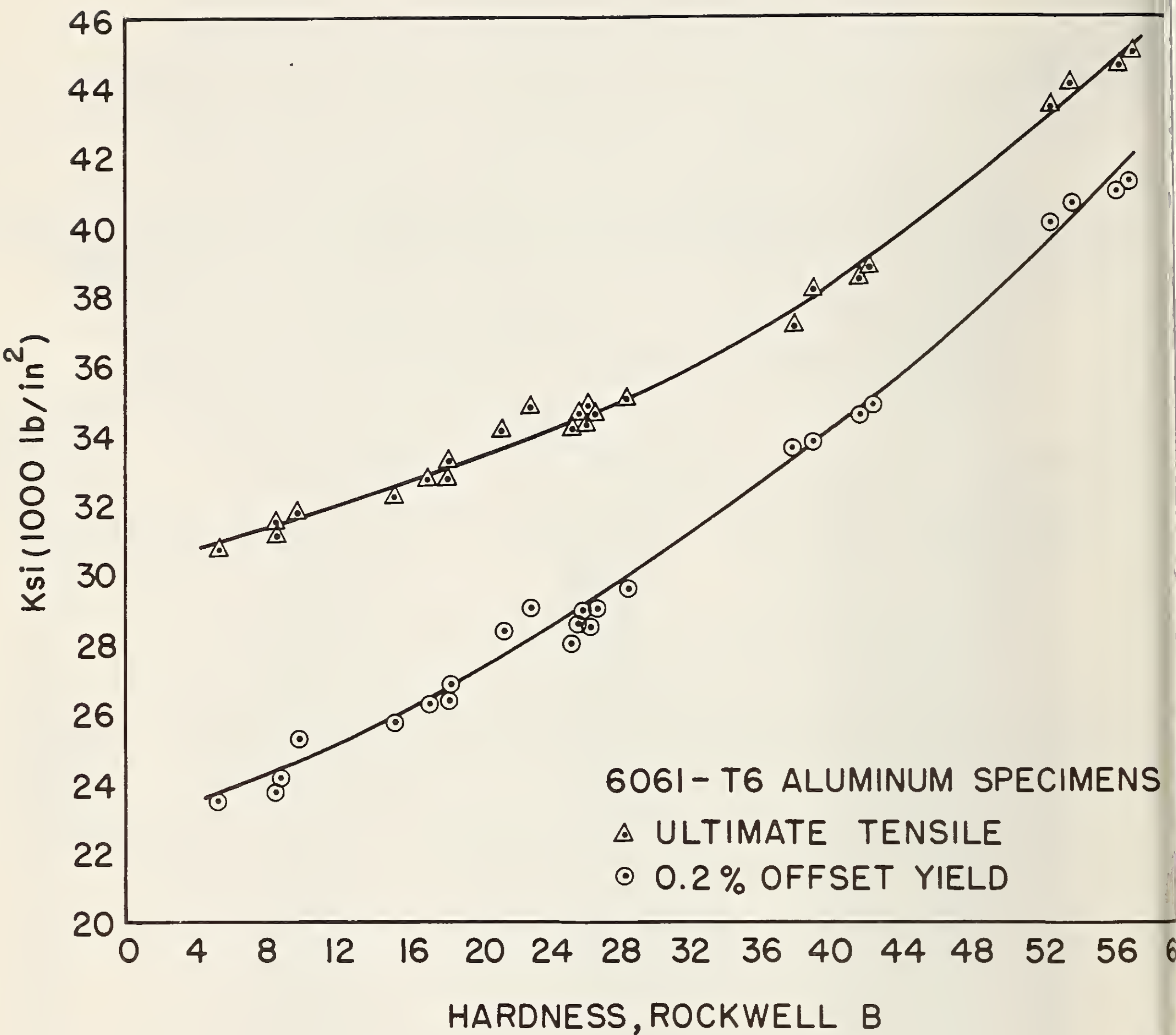

Figure D-1. Relationship of hardness to tensile strength and yield strength for 6061-T6 aluminum alloy.

REFERENCES

[1] "Fire Service Ladder Practices," validated by the International Fire Service Training Association, published by the Department of Fire Protection, Oklahoma State University (1969).

[2] NFPA No. 193-1972 "Standard on Fire Department Ladders - Ground and Aerial," published by the National Fire Protection Association, Boston, Mass. (1972).

[3] ANSI A14.2-1972, "American National Standard Safety Requirements for Portable Metal Ladders," published by American National Standards Institute, Inc., New York, N. Y. (1972).

[4] NFPA No. 19-1973 "Standard for Automotive Fire Apparatus," published by the National Fire Protection Association, Boston, Mass. (1973).

[5] Price, H. E., Crain, C. L. and Siciliani, F. A., "A Survey of Human Factors Engineering Problems in Firefighting Equipment," Final report on Office of Civil Defense (Dept. of Defense) Contract #OCD-PS-64-3 (Feb. 1964).

[6] Siegel, L. G., "The Projection of Flames from Burning Buildings," Fire Technology, 43-51, (Feb. 1969).

[7] Metals Handbook, 8th edition, American Society for Metals, Vol. 2, 276 (1964).

[8] Metals Handbook, 8th edition, American Society for Metals, Vol. 1, 525 (1961).

[9] Pearson, C. E. and Parkins, R. N., The Extrusion of Metals, 2nd edition (Wiley, New York, 1969).

[10] Metals Handbook, 8th edition, American Society for Metals, Vol. 2 (1964).

[11] Aluminum Standards and Data, 2nd edition, The Aluminum Association (1969).

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

The key performance requirements for fire department ground ladders were determined. Existing ladder standards were reviewed and found to be unnecessarily restrictive in some areas and inadequate and unrealistic in others. Included in the report are metallurgical studies of three ladders that failed in service as well as a correlation of hardness with tensile and yield strength for 6061-T6 alloy.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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