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RESEARCH MEMORANDUM

COMPARATIVE TENSILE STRENGTHS AT 1200° F OF VARIOUS ROOT DESIGNS FOR CERMET TURBINE BLADES

By Andre J. Meyer, Jr., Albert Kaufman
and Howard F. Calvert

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

Specimens of five different root designs, proportioned in accordance with the design curves, and specimens of a conventional fir-tree turbine root were fabricated from a titanium carbide cermet bonded with nickel. The comparative strengths were determined by short-time tensile tests at 1200° F. The results are compared with tensile tests on plastic models pulled at room temperature and with theoretical strengths based on design charts.

Three of the blade roots investigated showed ample strength to be suitable for operation in an aircraft jet engine. Specimens corresponding to rotor segments between adjacent blades of like design were tested in stress-to-rupture at 1200° F. These tests indicated an equivalent turbine rotor life of 850 hours for the dovetail design and over 1000 hours for the interlock design at rated speed of the J33-A-33 engine.

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INTRODUCTION

The aircraft turbojet industry is continually striving to increase the operating temperature of turbines so as to increase the thrust output of engines. Efforts are also in progress to reduce the strategic alloy content of the turbine materials. Ceramics, cermets, intermetallics, and high-strength cast alloys are some of the newer materials devised to help attain these goals. All the new materials, however, have the disadvantages of increased brittleness and high notch sensitivity. These factors change the design criteria used in devising means of attaching the blades to the rotor. Many of the conventional alloys are sufficiently ductile that the strength is not greatly reduced by the depth or sharpness of notches as long as large-magnitude vibrations are not acting on the blade roots. The strength of the new brittle materials, however, is very largely a function of notch radius and notch depth.

The investigation reported in reference 1 was conducted to determine the best geometric proportions for brittle-material roots and to evaluate the relative strengths of different root designs through tensile tests of plastic models. In the present investigation, which was conducted at the NACA Lewis laboratory, the four most practical designs, as determined by tensile tests, were fabricated from a titanium carbide plus nickel cermet. The results of short-time tensile tests conducted at 1200° F on the cermet specimens are reported herein.

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The blade roots were designed to be as strong as possible by maintaining a minimum margin of safety for the rotor segments between adjacent blades yet keeping the standard number of blades on the rotor. To assure sufficient rotor strength, stress-to-rupture tests were conducted on specimens made from conventional turbine-rotor materials. These data were also obtained at 1200° F (the rim temperature measured with metal blades at full power (ref. 2)).

BLADE-ROOT SPECIMENS

Specimens of the five types of root design investigated are shown in figure 1. The root-profile dimensions are shown in figure 2. These dimensions are based on calculations from the design charts presented in reference 1 and on the J33-A-33 turbojet engine, which has a 54-blade turbine rotor with a tip diameter of 26.5 inches and a rim thickness of 1.96 inches. The length of the airfoil above the platform is 4.250 inches and its shape is the same as that of a mass-production metal blade. The roots were designed to operate at 11,750 rpm, the take-off speed of the engine. The specimens were the same size as those used in a turbine, but the thickness was limited to 5/8 inch because of the limiting load capacity and furnace size of the stress-rupture machines used in some of the tests.

In the design investigation (ref. 1) it was concluded that, for brittle-material blade roots, the notch radius should be made large, the notch depth should be as small as practical, and for these shallow notches the ratio of notch radius to neck distance should be as large as possible; another factor considered in establishing root shape is the ease of machining. One or more of these principal objectives were observed in designing the blade roots tested. The reasoning behind the design of the roots, which is discussed in reference 1, is briefly reviewed in the following paragraphs.

<u>Modified fir tree</u>. - The modified fir-tree root closely resembles the conventional fir-tree root except that the radii between serrations were increased from 0.025 to 0.135 inch.

Four pin. - Ease of fabrication was the primary factor on which the four-pin design was based. With the space limitations imposed by the turbine design, it was impossible to obtain sufficient strength with a single pair of pins. To assure approximately equal loading of each pair of pins, the pins were made more ductile than the wheel material; therefore, they readily deformed under load and produced 100 percent bearing at the contact surfaces.

Dovetail. - Actually two configurations of the dovetail root were evaluated. In both configurations, the notch depth was reduced to permit a large ratio of notch radius to neck distance. One root was so designed that large-diameter milling cutters could be used to machine the root recesses in the wheel rim rather than small-end mill-type cutters or expensive broaches. The other configuration was proportioned in accordance with the optimum ratios as established in reference 1.

Interlock. - At the expense of neck distance, the interlock root incorporates the largest notch radius investigated, thus giving a high notch-radius-to-neck-distance ratio. Again, ductile inserts were used to distribute the load over the bearing surfaces and thus to compensate for the lack of ductility in the cermet. Machining of the rotor is easiest and least expensive for this design. Only a drilling operation followed by roughing out the remainder of the opening is required. Furthermore, the blade can pivot in its socket and thus can be automatically self-alining according to the operating forces acting on the airfoil.

Materials. - The cermet specimens were fabricated from a material consisting of 62 percent titanium carbide, 30 percent nickel, and 8 percent a solid solution of columbium, tantalum, and titanium carbides added to increase the resistance to oxidation. The cermet components of the specimens simulating the turbine blades were produced by Kennametal, Inc. and are shown in the upper half of figure 1. All specimens were inspected by the penetrant oil method. The mating parts of the specimens, shown in the lower half of the figure, were made at the Lewis laboratory from Timken Alloy 16-25-6, a widely used rotor material. These parts for the fir-tree designs were fabricated in two pieces to facilitate form grinding of the complex shapes. They were held together by Inconel bolts during the tensile tests.

Austenitic stainless steels were used, in making the ductile inserts for the interlock and the four-pin-root designs. To investigate the effect of a soft cushioning material, electro-formed nickel-plated copper screen made by the Electromesh Co. was inserted between the blade root and the rotor specimen of all designs.

Rotor Specimens

The blade-root profiles were made as wide as practical while still maintaining a reasonable strength in the turbine rotor. In order to verify that sufficient strength had been retained in the rotor, specimens (Timken 16-25-6) simulating rotor segments of the most critical designs, the interlock and one of the dovetail configurations, were subjected to stress-to-rupture tests. For comparison, specimens of the conventional fir-tree cut from a production turbine rotor were also tested. Samples of all three rotor specimens are shown in figure 3.

APPARATUS AND PROCEDURE

The loading fixtures used for pulling the specimens are shown in figure 4. Heat-treated Inconel X grips were engaged with the T-head of the specimen, and a stainless-steel ring was placed around the grip to prevent its spreading under load. Circular segments were fitted in the voids between the ring and the sides of the grip. A rectangular collar made of S-816 was slipped over the rotor segments to prevent spreading of the root opening. Double-pinned joints were provided above and below the specimen to minimize bending loads.

The assemblies were tested in either a 20,000-pound screw-type stress-rupture machine or a 400,000-pound universal hydraulic tensile machine. The specimens were heated to 1200° F in automatically controlled furnaces. The temperature was measured by a chromel-alumel thermocouple at the neck or at the expected location of failure of the specimens and, after the temperature was well stabilized, the load was increased until fracture occurred. The specimens for simulating turbine rotor segments were loaded at values less than the short-time ultimate tensile load and the varying times to rupture were recorded.

RESULTS AND DISCUSSION

Blade Root Evaluation

The results of the tensile tests are summarized in table I together with the important dimensions for each blade-root design and its theoretical rupture strength based on reference 1. (The symbols used in this report are defined in the appendix.) The experimental data presented in table I are averages obtained with several specimens. The actual loads of the individual specimens are presented in table II. For convenience, the design chart in reference 1 used to compute the theoretical strengths is reproduced in figure 5. In the calculations of strength of the multiple land roots, the strength of only the land nearest to the airfoil was determined. The theoretical and experimental loads given in tables I and II have been adjusted for the full root thickness of 1.960 inches. Also listed in table I are the operating stresses in the blade-root neck and in the adjacent rotor segment that each root type would be subjected to because of centrifugal loading at the full rated speed of the engine.

The experimental results plus the theoretical and operating loads for each design are plotted in figure 6. The theoretical load was determined from figure 5, where for a particular design any two of the five dimensionless parameters listed in table I can be used to determine the load carrying factor $\frac{d}{D\ K_f}$ from the chart. When this factor is multiplied by the tensile stress of the material, the root thickness, and the over-all root width, the theoretical load for the design is obtained. A detailed description of this procedure is given in reference 1.

From figure 6 it can be seen that the experimental rupture loads of the root designs were lower than the theoretically predicted values, although without screen the interlock and four-pin roots, which have ductile pins inherent in the design, were fairly close. The failure of the fir-tree, modified fir-tree, and dovetail designs to attain the theoretical loads without screen is primarily due to local surface irregularities which are to be expected because of limitations in machining accuracy. These irregularities cannot be compensated for by deformation of the material under load, since cermets are almost completely lacking in ductility even at 1200° F.

The importance of bearing area and gradually varying load over the full notch depth is borne out by the marked improvement in the fir tree, modified fir-tree, and dovetail designs when nickel-plated copper screen is placed around the root notches. There is a large improvement in the load-carrying capacity of the dovetail roots as figure 6 shows. These roots were the strongest ones tested. As would be expected, the increase in strength of the interlock design resulting from the use of screen was not as large as in the other designs because a relatively ductile material had already been inserted in the assembly.

The four-pin design also had soft ductile pins, which, when load was applied, conformed to any high or low asperities or other irregularities in the bearing surfaces of the cermet. The addition of copper screen caused a loss of strength in this design probably because the pins were made appreciably smaller in order to fit the screen between the pins and the recesses. This resulted in a reduction in bearing area since the maximum possible bearing area equaled the lengthwise projected area of the pin. There may also have been a loss in effective bearing area because of the porosity of the screen.

Three types of screen were used: 25, 40, and 65 mesh, all from 0.005 to 0.0065 inch in thickness. No difference in load-carrying capacity could be detected among the three types; hence, when the experimental loads were averaged for any design in which screen was used, all were averaged together.

Except for the modified fir-tree root, the rupture loads when screening was used, and in the case of the four-pin root without screen, were within 12 percent of the theoretical loads. The discrepancy between the experimental fracture loads and the theoretically predicted values may be due to several factors. The principal factor that tends to reduce the experimental loads is the effect of loading the specimen within the notches. This loading introduces compression on the bearing surfaces and, as shown in reference 1, results in a lower load-carrying capacity than would be obtained by the pure tensile loading assumed in the derivation of the theoretical load-carrying capacity. Also, the slightest flaws or defects in brittle materials are very detrimental compared with corresponding effects in ductile materials. Furthermore, the bending stresses introduced by even slight assymmetrical loading greatly reduces the ultimate rupture load for brittle materials, as pointed out in reference 3. If these facts and the differences in shape of the various designs from the theoretically ideal notched tensile specimen are considered, the agreement between the experimental results and notch theory is very good.

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Distributing the load between more than one pair of lands does not seem to increase the load-carrying capacity of a root to any considerable extent. The probable explanation for this is the physical impossibility of machining the steps so that they are all equally stressed when a load is applied. Even the addition of the ductile screen which would tend to squeeze out around high spots or fill in low spots on the bearing surface did not seem to improve this condition. This fact is demonstrated by the following experiment:

A number of fir-tree specimens including some with screen and some without were heated to 1200° F and load was applied until a noise or a drop in load indicated that a failure had occurred even though the specimen might still be holding together. All load was then released, the heat was turned off, and the specimen was disassembled. When it was found that some land other than the top one had failed, the specimen was reassembled, reheated, and reloaded until failure again occurred. This process was repeated until final failure occurred at the top serration of the specimen. In some cases a series of as many as four failures occurred before the top section ruptured. In each case, however, it was found that the applied load at which each partial failure occurred in subsequent loading was approximately the same as the load at the initial failure. It might also be added that the machining fits of the mating parts used in this test were probably better than could be reasonably expected in normal production.

Theoretically, the modified fir tree has the second largest load-carrying capacity of all the designs investigated, but in the actual tests it proved to be the weakest even when screen was used, (fig. 6). This weakness was partially attributed to poorer quality material, since under penetrant oil inspection all the specimens of this design as received from the manufacturer showed a high degree of surface porosity. Also, the tensile tests on these specimens showed an unusual amount of scatter, amounting to 28 percent when no screen was present.

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For a comparison of the relative merits of these roots, it is not sufficient to compare only the failure loads. Another important factor is the operating load that each design must withstand at rated speed of the engine. This load will vary somewhat with each design because the profile area of the root between the platform and the neck varies to some extent; the mass of the root above the neck and the location of the center of gravity of the blade is therefore different for each design. The operating loads are also plotted in figure 6.

The merits of each design can be more readily evaluated with the aid of figure 7. The ordinate is the ratio of the failure load to the operating load. When no screen is used, it is evident that the interlock is the strongest design, but when screen is added, the optimum dovetail is the strongest; the other dovetail and the interlock have slightly lower strength values.

The results of the tensile tests of the cermet blade roots are compared in figure 8 with the results for the plastic models reported in reference 1. The ratio of the fracture stress to the ultimate tensile stress of the plastics is plotted against a similar ratio for the cermet fir tree, modified fir tree, optimum dovetail, dovetail, and interlock roots (all with screen) and the four-pin root without screen. Since the ordinate and abscissa scales are the same, perfect correlation would show all the points falling on the 45° line. The figure shows that the correlation between the cermet tests at 1200° F and the plastic tests at room temperature is good except for the modified fir-tree design. Thus, tensile tests of plastic models seem to be suitable qualitative criteria of the strength of blade-root designs for brittle materials.

ROTOR-SEGMENT EVALUATION

The strength of cermets is not greatly affected by time at 1200° F; however, the strength of wheel materials is largely a function of the amount of time the load is applied. Because short-time tests will not suffice, rotor strengths were evaluated by stress-rupture tests carried out on the rotor segments between two adjacent dovetail, interlock, or standard fir-tree roots. The results are tabulated in table III and are shown in figure 9 where average stress in the neck is plotted against time to rupture. In the dovetail and interlock designs, the notch radii are fairly large and have little effect on the strength of the rotor material (Timken 16-25-6). The fir-tree design with a smaller notch radius does seem to have a small effect on the strength of Timken 16-25-6 as evidenced in figure 9 by the curve for the fir-tree wheel segments, which is slightly below the curves for the interlock and dovetail segments.

The horizontal lines in figure 9 represent the operating tensile stresses in the rotor segment at full rated speed when cermet blades are used. At the operating conditions, the fir tree and the interlock rotor segments show an equivalent life of over 1000 hours and the dovetail shows a life of 850 hours.

It may seem that the operating stress in the fir-tree segment is relatively low and that the strength of the blade root could be increased by expanding the root and thus reducing the rotor area. The rotor stress shown, however, is for the neck farthest from the rim, the serration which consistantly failed, while the blade strength can be increased only by increasing the width of the neck nearest the rim. The rotor neck nearest the rim is already very narrow; therefore, a slight increase in blade neck, and consequently a very slight increase in blade strength, could be obtained only at the expense of a large reduction in rotor strength at that point.

In figure 9, the life of each of the three rotor segments investigated is compared with the life of a conventional J33 turbine rotor with metal blades; stress-rupture tests indicate that the life of this rotor is about 500 hours at rated speed. The strengths of the dovetail, interlock, and fir-tree rotor segments apparently are ample for use in a standard J33 rotor.

CONCLUSIONS

From short-time tensile tests of cermet blade-root specimens, the following conclusions were obtained:

1. The use of screen around the blade root increases the load-carrying capacity appreciably in any design in which no ductile material was originally present.

2. When screen is not used, those designs which incorporate ductile pins between blade and rotor parts show the highest relative strength.

3. Of the six roots investigated, the dovetail proportioned according to optimum design ratios and used with screen possesses the greatest strength. Another dovetail design and the interlock root had slightly lower strength values.

4. The theoretical design charts based on symmetrically notched tensile specimens are a fairly good basis on which to design blade roots even when the shapes are radically different.

5. Short-time tensile tests of models made from a plastic give a good qualitative indication of the merits of various cermet blade roots.

6. Additional lands or pairs of notches do not appear to increase the strength of the roots.

7. The rotor segments between adjacent dovetail or interlock blade roots as designed herein have ample strength for use in turbojet aircraft engines.

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National Advisory Committee for Aeronautics
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APPENDIX - SYMBOLS

The following symbols are used in the tables and figures included in this report:

d minimum width or neck distances between notches, in.

D over-all width of blade root, in.

t thickness, in.

r radius of notch, in.

h notch depth, in.

K_f stress concentration factor

S_t ultimate tensile stress of material, psi

P load, lb

P_t theoretical rupture load, lb

P_r experimental rupture load, lb

P_o operating load, lb

S_r experimental rupture stress, psi

S_o operating stress, psi

Subscripts:

1 without screen

2 with screen

REFERENCES

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2. Farmer, J. Elmo, Millenson, M. B., and Manson, S. S.: Study of Stress States in Gas-Turbine Disk as Determined from Measured Operating-Temperature Distributions. NACA RM E8C16, 1948.

3. Duckworth, W. K., Schwope, A. D., Johnston, J. K., Stockett, S. J., Roberts, J. L., and Schofield, H. Z.: Mechanical Property Tests on Ceramic Bodies. A. F. Tech. Rep. No. 6512, Battelle Memorial Inst., U.S.A.F. Air Materiel Command, Wright-Patterson Air Force Base, Dayton (Ohio), Apr. 1951.

TABLE I. - DIMENSIONS AND STRENGTHS OF ROOT SPECIMENS

[Data adjusted to full root thickness of 1.960 in.; tensile strength S_t, 74,000 psi.]

Root design	Neck width, d, in.	Over-all width, D, in.	Notch radius, r, in.	Notch depth, h, in.	Dimensionless parameters (a) r/D	h/D	d/D	r/h	r/d	Load factor, d/DK_f (a)	Theoretical rupture strength, P_t, lb (b)	Experimental rupture strength without screen, $P_{r,1}$ lb
Fir tree	0.681	0.811	0.025	0.065	0.031	0.080	0.840	0.385	0.037	0.240	28,230	19,480
Modified fir tree	.549	.800	.135	.126	.169	.158	.686	1.071	.246	.356	41,310	17,360
Four pin	.409	.560	.110	.076	.196	.136	.730	1.447	.269	.404	32,810	29,960
Dovetail	.438	.667	.156	.115	.234	.172	.657	1.357	.356	.392	37,920	23,950
Interlock	.379	.600	.313	.111	.522	.185	.632	2.820	.826	.468	40,730	34,140
Optimum dovetail	.405	.623	.280	.109	.449	.175	.650	2.569	.691	.463	41,840	21,040

Root design	Experimental rupture strength with screen, $P_{r,2}$, lb	$\frac{P_{r,max}}{P_t}$	Operating load, P_o, lb	$\frac{P_{r,1}}{P_o}$	$\frac{P_{r,2}}{P_o}$	Rupture stress without screen, $S_{r,1}$, psi	Rupture stress with screen, $S_{r,2}$, psi	$\frac{S_{r,max}}{S_t}$	Operating rotor stress, S_o, psi	Operating-blade root stress, S_o, psi
Fir tree	24,860	0.881	14,050	1.386	1.769	14,570	18,850	0.251	23,280	14,270
Modified fir tree	22,180	.537	15,760	1.102	1.407	16,120	20,560	.278	34,280	14,650
Four pin	20,760	.913	14,560	2.058	1.426	37,300	25,760	.504	32,850	18,160
Dovetail	37,190	.981	15,040	1.592	2.473	27,850	43,330	.586	34,780	17,520
Interlock	36,380	.893	15,180	2.249	2.397	45,790	48,350	.653	31,640	25,790
Optimum dovetail	41,220	.985	15,100	1.393	2.730	26,060	51,040	.690	35,530	19,020

[a]Ref. 1.

[b]Calculated on basis of ref. 1.

TABLE II. - CERMET-SPECIMEN DATA

[Data adjusted to full root thickness of 1.960 in.; tensile strength S_t, 74,000 psi.]

Root design	Load without screen, P_r, lb	Load with screen, P_r, lb	Stress without screen, S_r, psi	Stress with screen, S_r, psi	Maximum scatter of stress without screen, percent	Maximum scatter of stress with screen, percent
Fir tree	20,320	27,600	15,180	20,560		
	16,460	27,880	12,320	20,870		
	21,640	26,840	16,200	20,090		
	------	22,050	------	16,460		
	------	19,950	------	14,930		
Av.	19,480	24,860	14,570	18,580	15.4	19.6
Modified fir tree	13,110	19,220	12,150	17,870		
	13,270	24,680	12,410	22,870		
	22,270	22,030	20,640	20,480		
	20,790	24,710	19,270	22,780		
	------	20,260	------	18,780		
Av.	17,360	22,180	16,120	20,560	28.0	13.1
Four pin	27,470	19,690	34,090	24,440		
	21,070	21,830	26,250	27,080		
	29,100	------	36,250	------		
	37,410	------	46,780	------		
	34,750	------	43,110	------		
Av.	29,960	20,760	37,300	25,760	29.6	5.1
Dovetail	23,440	37,880	27,180	43,930		
	24,210	37,890	28,180	45,090		
	24,210	34,810	28,180	40,960		
Av.	23,950	37,190	27,850	43,330	2.4	5.5
Interlock	33,430	36,380	44,980	48,350		
	33,590	------	44,810	------		
	35,500	------	48,170	------		
	34,030	------	45,210	------		
Av.	34,140	36,380	45,790	48,350	5.2	-----
Optimum dovetail	21,010	39,510	26,070	49,030		
	21,070	49,240	26,050	60,850		
	------	46,730	------	58,200		
	------	39,200	------	48,450		
	------	34,500	------	42,640		
	------	41,080	------	50,580		
	------	38,390	------	47,810		
	------	41,080	------	50,780		
Av.	21,040	41,220	26,060	51,040	.1	19.2

TABLE III. - WHEEL-SPECIMEN DATA

[Data adjusted to full root thickness of 1.960 in.]

Root design	Load, P_r, lb	Area, sq in.	Stress, S_r, psi	Time, hr
Fir tree	85,480	1.183	72,230	(a)
	72,150	1.190	60,650	1.2
	68,380	1.197	57,140	3.5
	59,600	1.181	50,470	9.0
	50,970	1.185	43,010	33.1
	41,250	1.194	34,540	162.3
Dovetail	54,880	.599	91,620	(a)
	40,140	.601	66,770	1.3
	35,940	.594	60,507	4.0
	33,430	.601	55,670	11.2
	30,290	.599	50,580	10.7
	30,170	.593	50,870	19.0
	27,600	.601	45,880	71.2
	26,500	.601	44,130	70.3
	23,390	.599	39,060	534.8
Interlock	67,660	.713	94,840	(a)
	63,350	.714	88,670	(a)
	60,840	.713	85,350	.2
	53,470	.716	74,680	1.2
	44,910	.715	62,780	4.0
	41,900	.716	58,550	10.5
	39,200	.715	54,830	13.8
	37,570	.716	52,450	24.2
	35,060	.712	49,270	53.1
	30,920	.714	43,300	224.7

[a]Short-time tensile test.

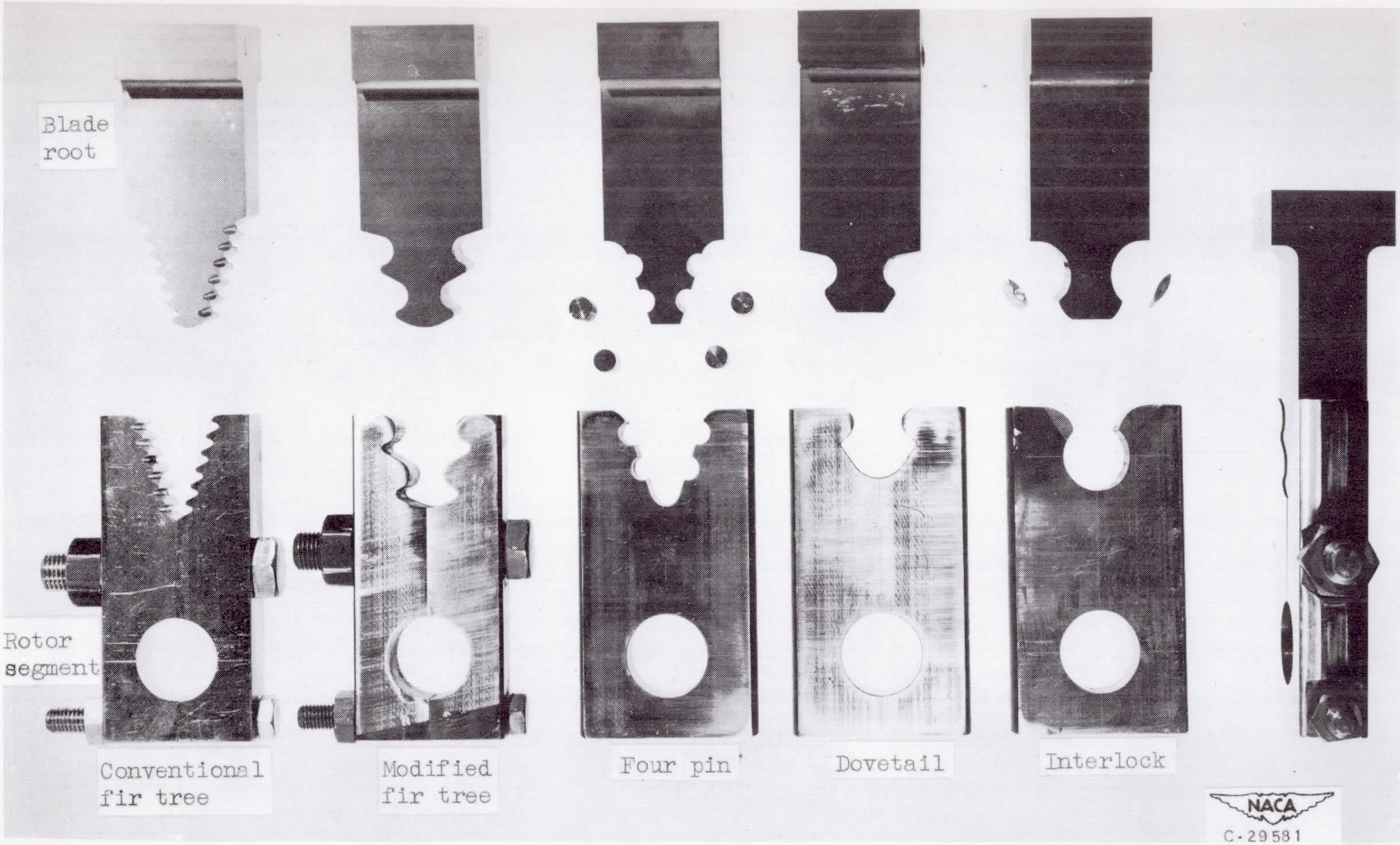

Figure 1. - Root specimens used in this investigation.

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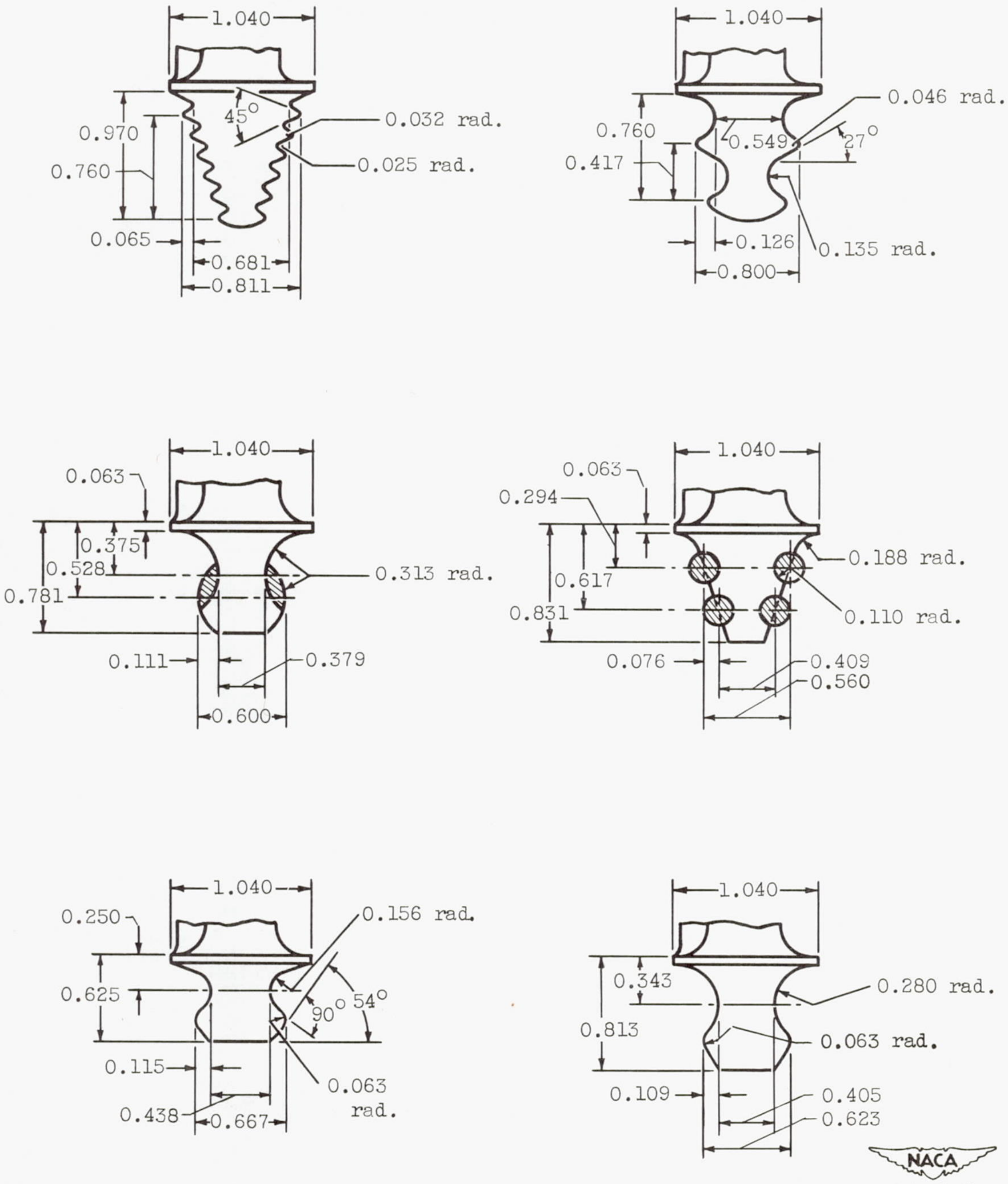

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Figure 2. - Dimensioned sketches of root profiles. (All dimensions in inches.)

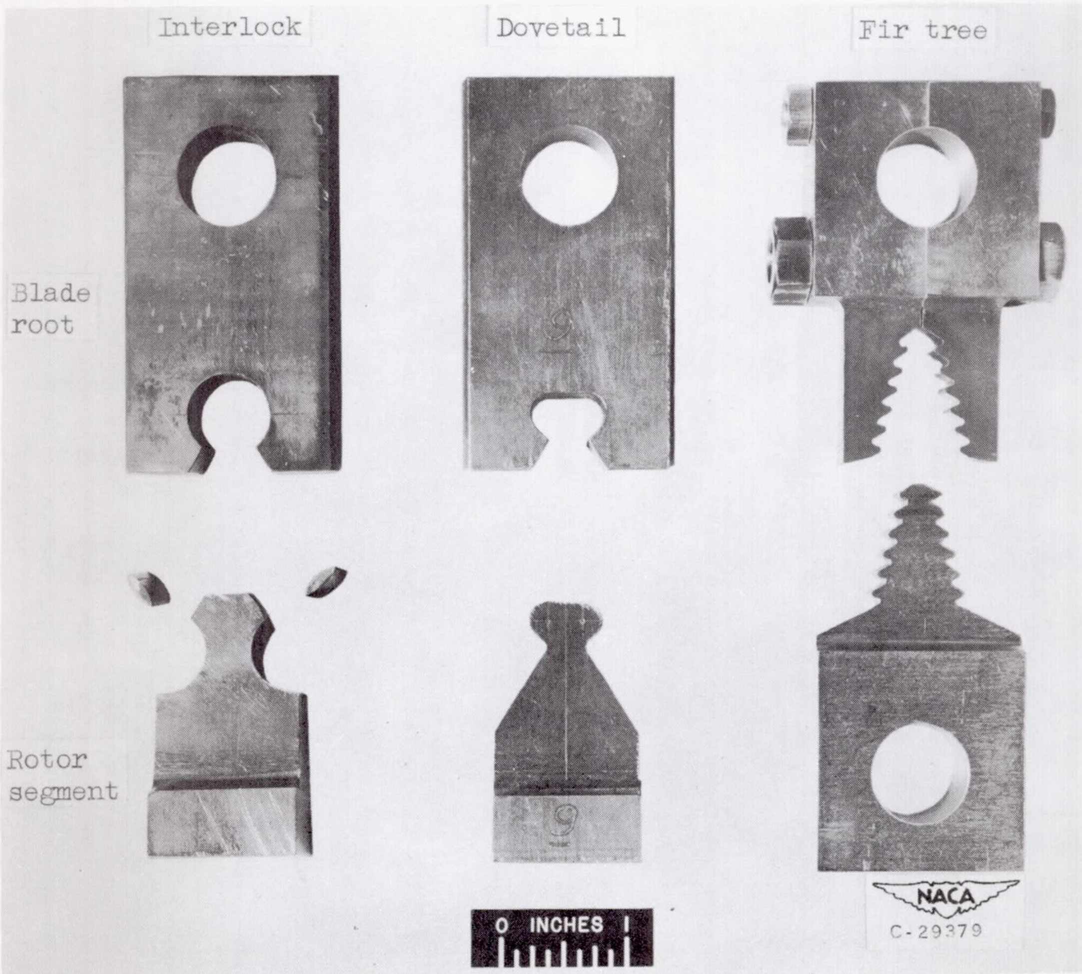

Figure 3. - Turbine rotor segment specimens.

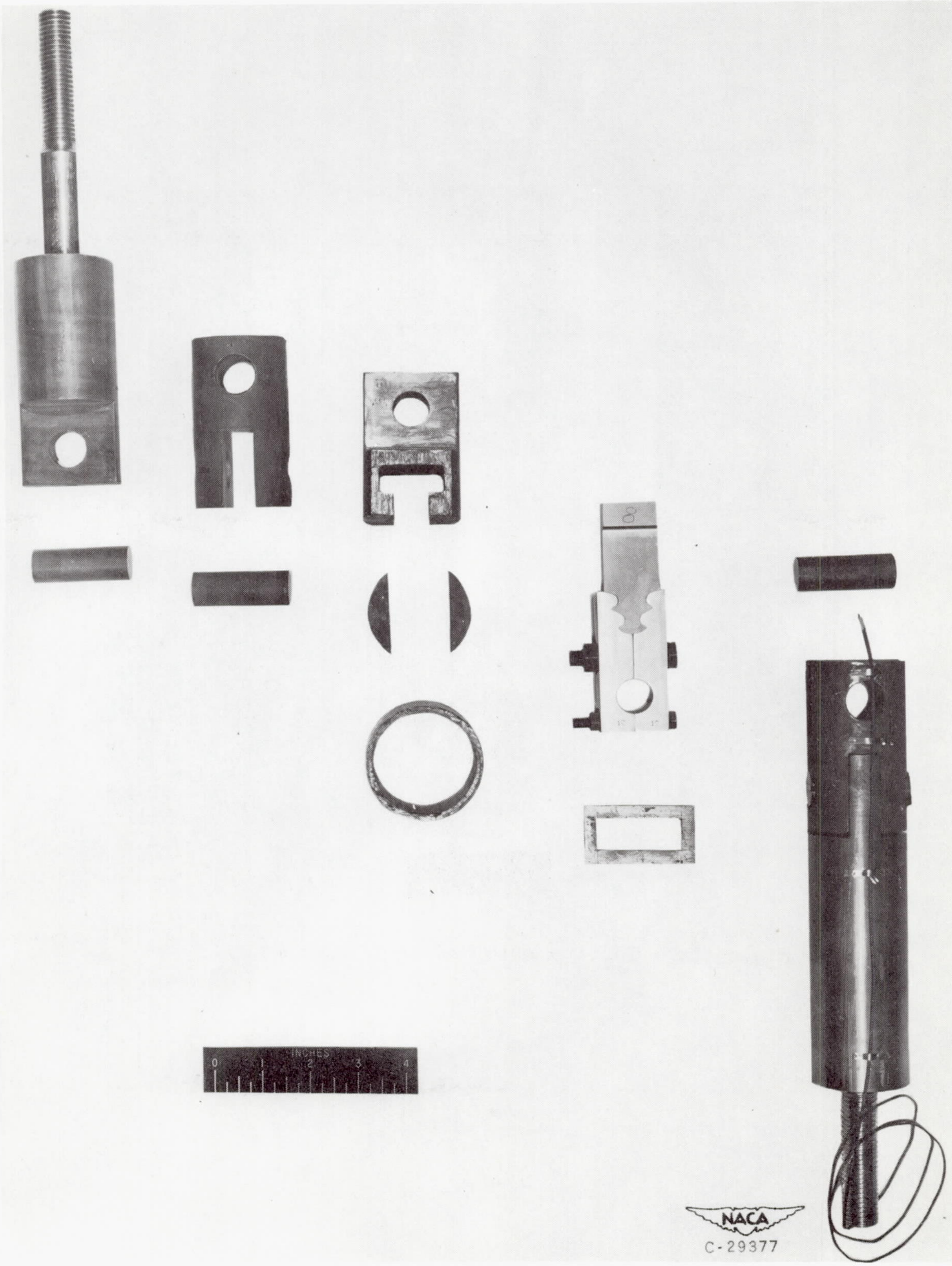

Figure 4. - Loading fixtures.

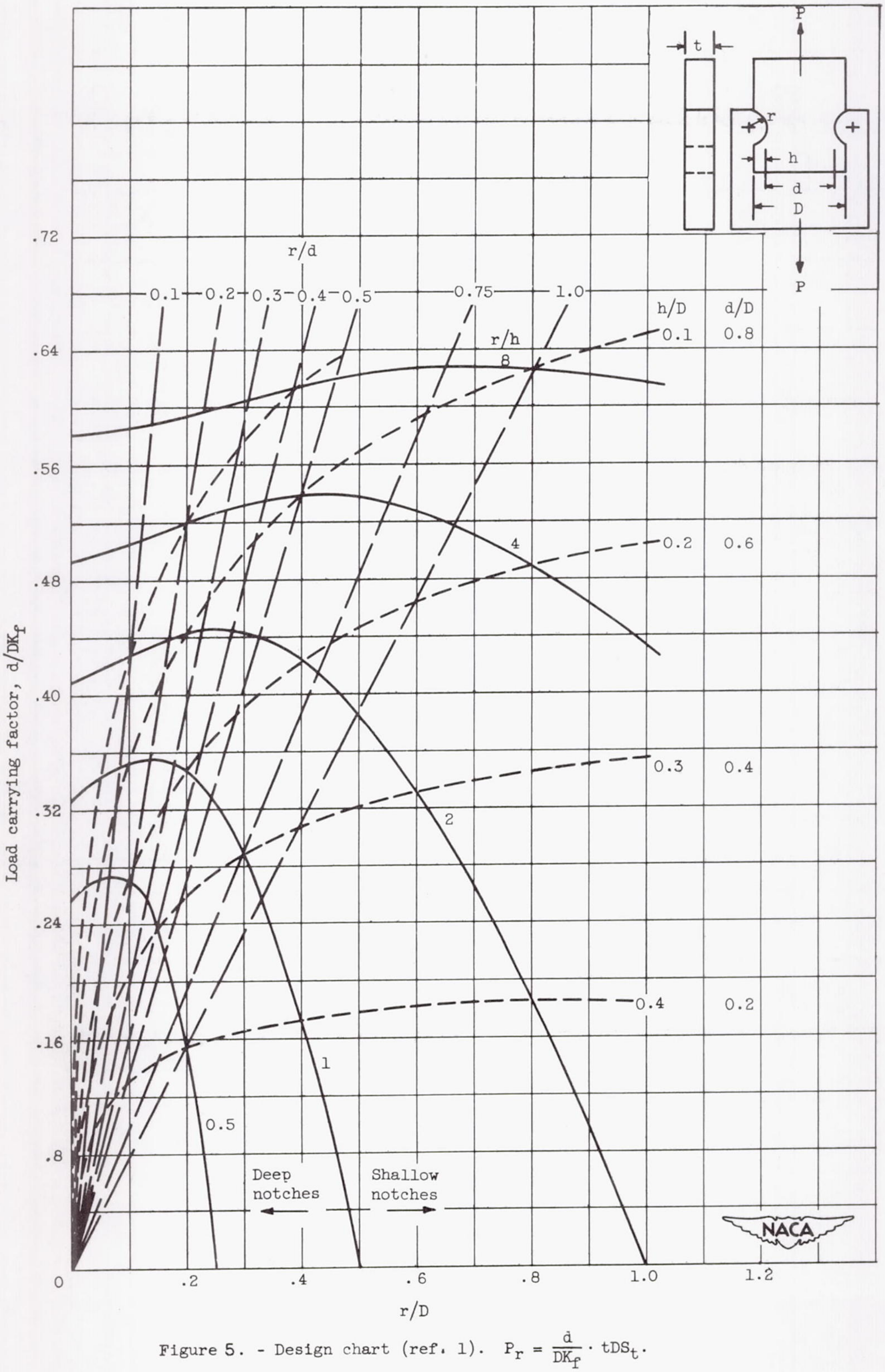

Figure 5. - Design chart (ref. 1). $P_r = \frac{d}{DK_f} \cdot tDS_t$.

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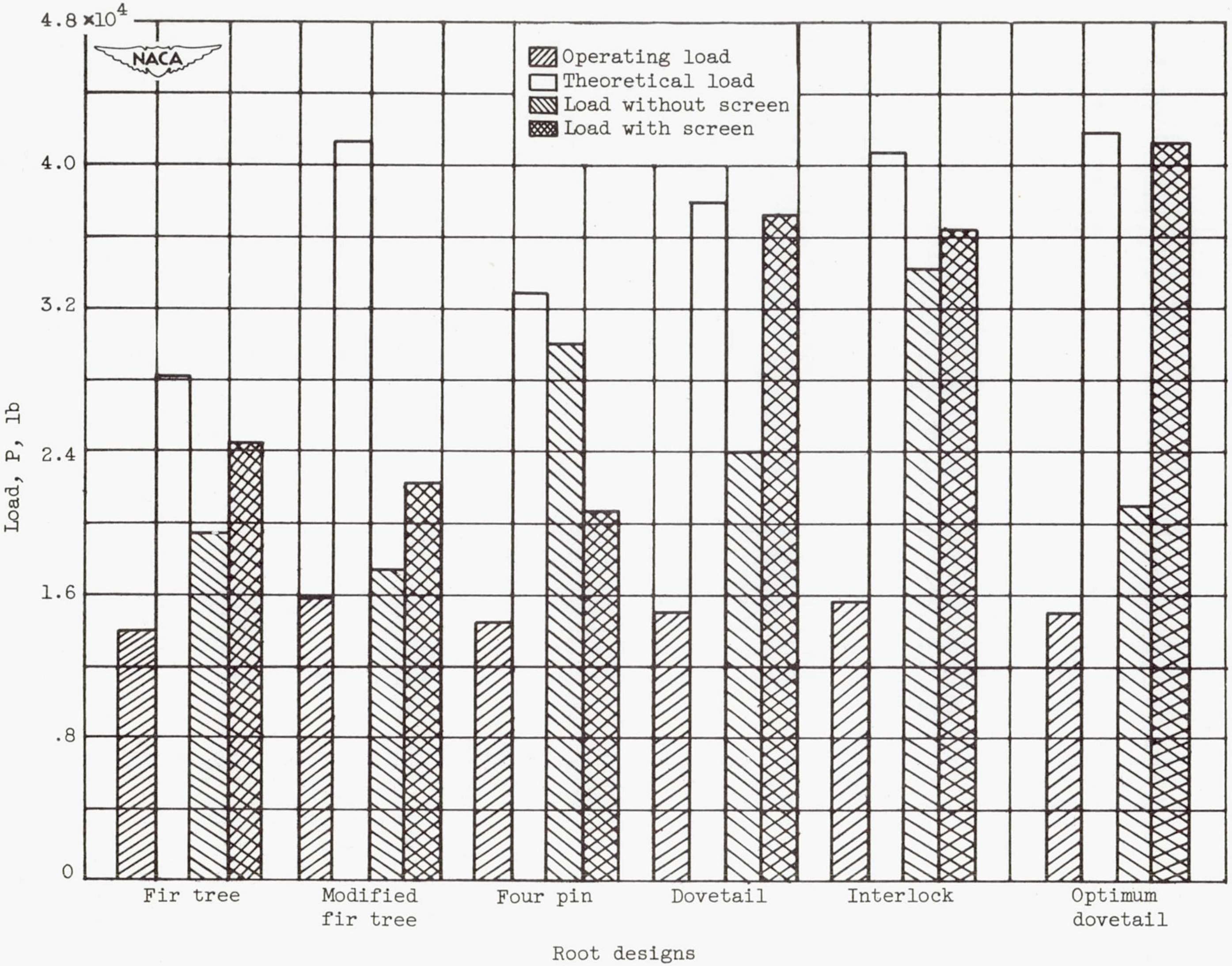

Figure 6. - Comparison of experimental results with theory.

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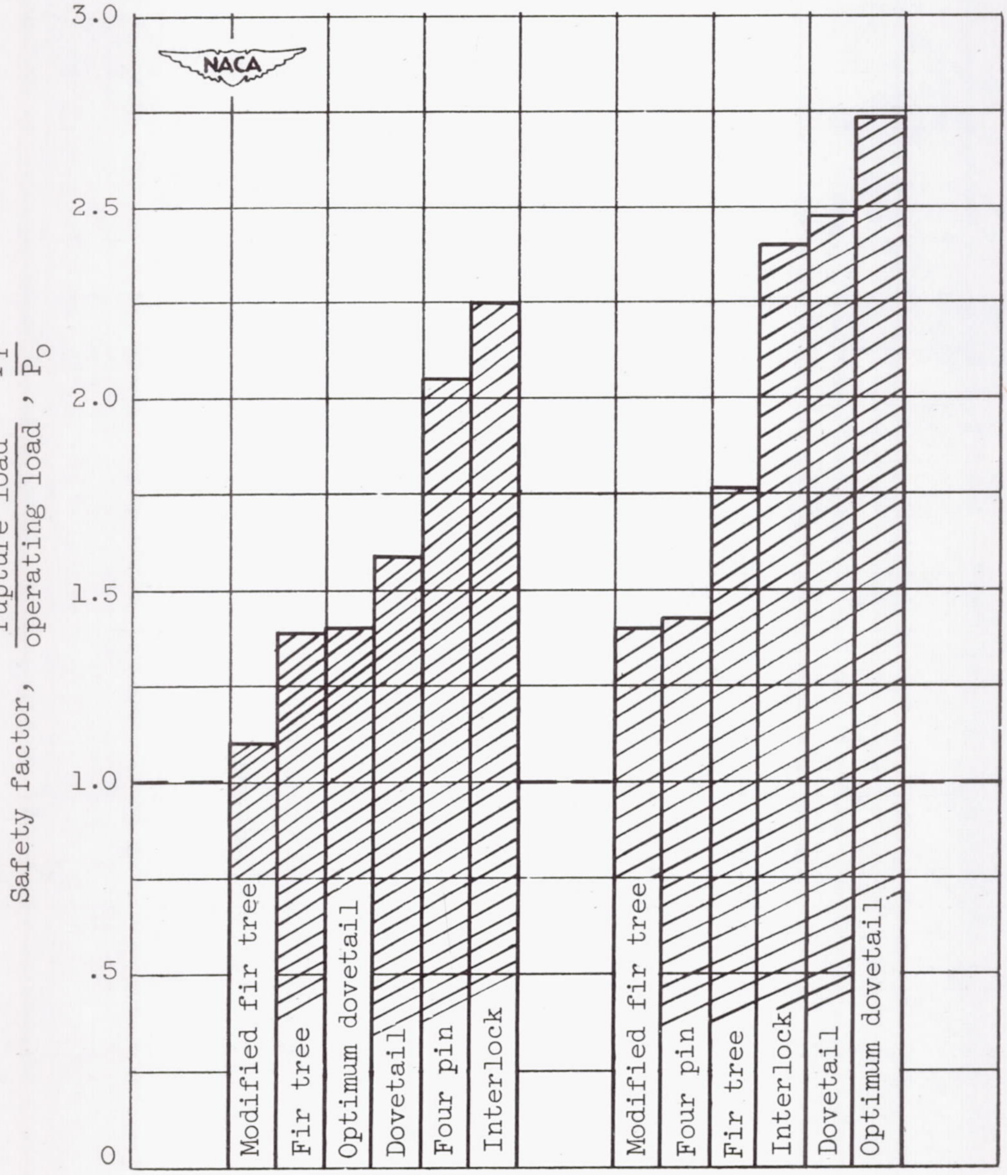

(a) Without screen. (b) With screen.

Figure 7. - Comparison of safety factors for cermet root designs with and without screen.

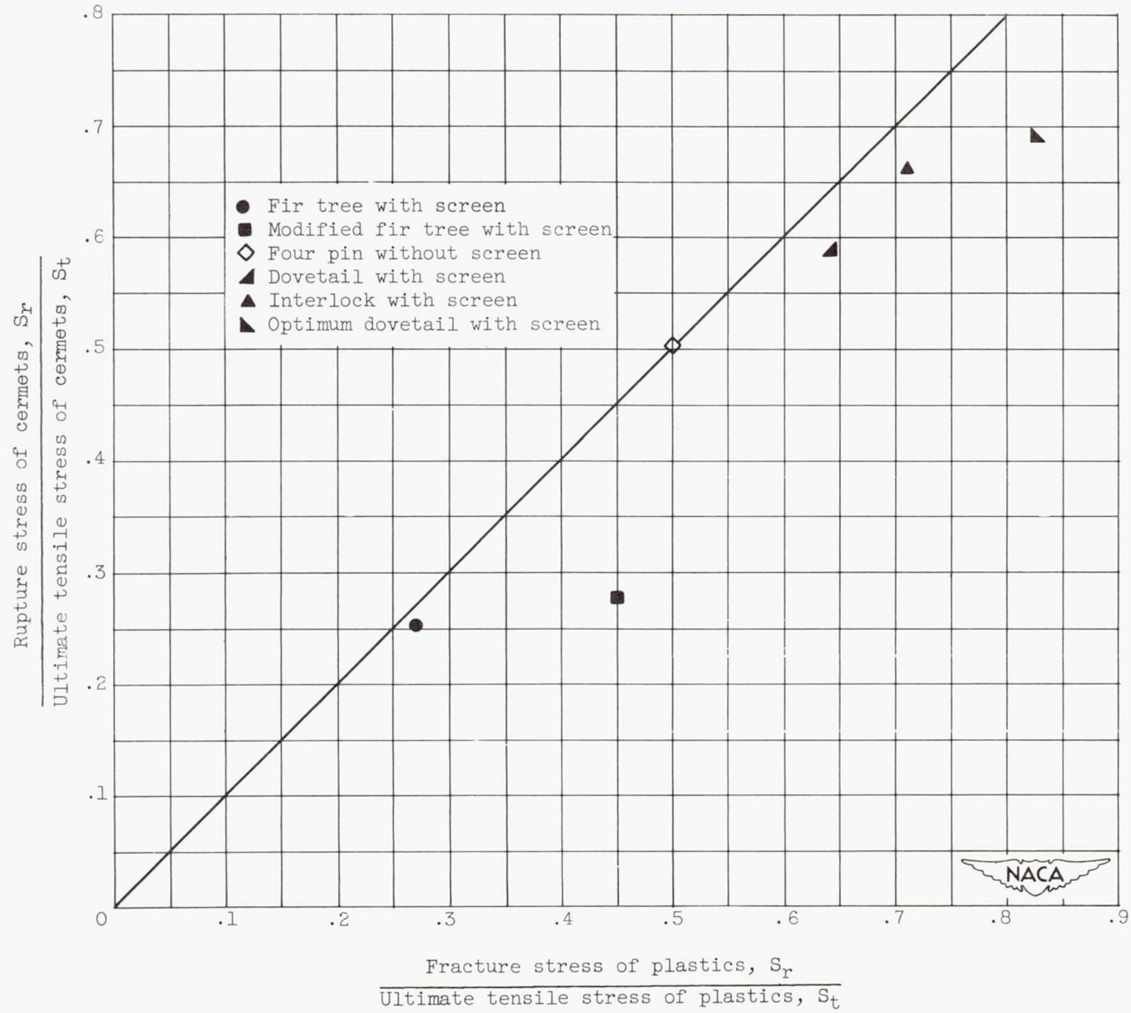

Figure 8. - Comparison of relative strengths of plastic and cermet root specimens. Plastics at room temperature, cermets at 1200° F.

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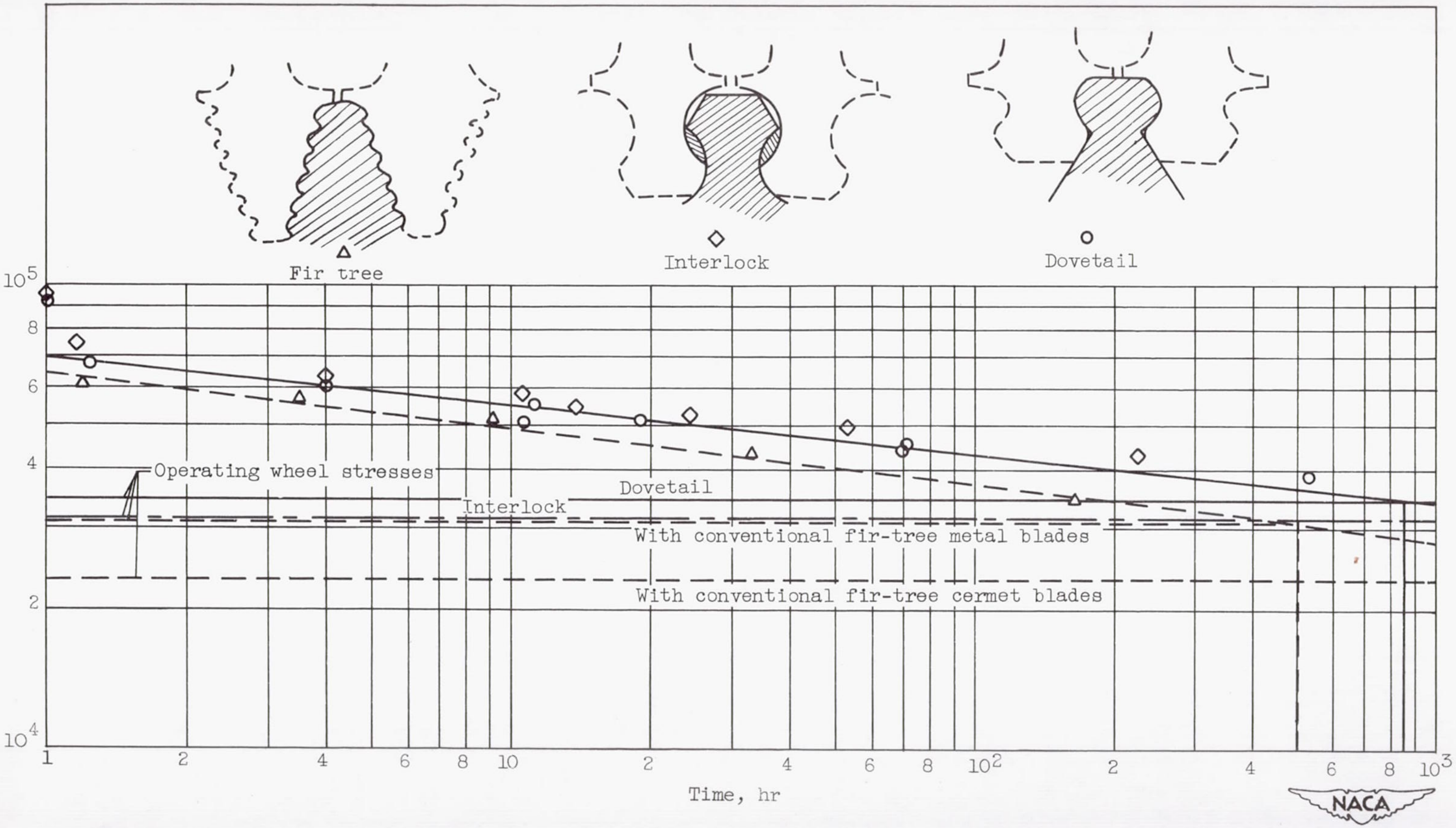

Figure 9. - Effect of stress on rupture life of rotor segments. Material Timken, 16-25-6; temperature, 1200° F; speed, 11,750 rpm.

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