To be presented at Western Regional
Strain Gage Committee Meeting,
San Francisco, California
September 15-16, 1969

UCRL-18423 Rev.
Preprint

cy. 2

FATIGUE LIFE GAGES ON A 46,000 kVA GENERATOR UNDER PULSED LOADING

RECEIVED
LAWRENCE
RADIATION LABORATORY

SEP 1969

LIBRARY AND
DOCUMENTS SECTION

Roland S. Krevitt

August 1969

AEC Contract No. W-7405-eng-48

TWO-WEEK LOAN COPY

This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 5545

LRL

LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

UCRL-18423 Rev.

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

FATIGUE LIFE GAGES ON A 46 000 kVA GENERATOR UNDER PULSED LOADING*

Roland Krevitt

Lawrence Radiation Laboratory
University of California
Berkeley, California

August 1969

ABSTRACT

On December 19, 1966, near catastrophic fatigue failures in two 46000-kVA generators were discovered; a 6-month shutdown of a major nuclear physics research facility resulted. The cost of replacing the failed parts was $330 000.

The Bevatron, at the Lawrence Radiation Laboratory in Berkeley, California, is a proton accelerator. A large electromagnet guides the protons in a circular path, and because of the nature of the acceleration cycle, the magnet must be pulsed 11 times per minute with a peak coil current of 8 400 A and a peak voltage of 16 000 V. This results in a pulsed demand on the generators that supply power to the electromagnet, and causes severe stress in the generator armatures. These cyclic stresses led to fatigue failures.

This paper describes the use of S/N fatigue life gages to detect possible future armature fatigue damage.

INTRODUCTION

One of the major components of a machine that accelerates charged nuclear particles, such as the LRL Bevatron, is an electromagnet, whose

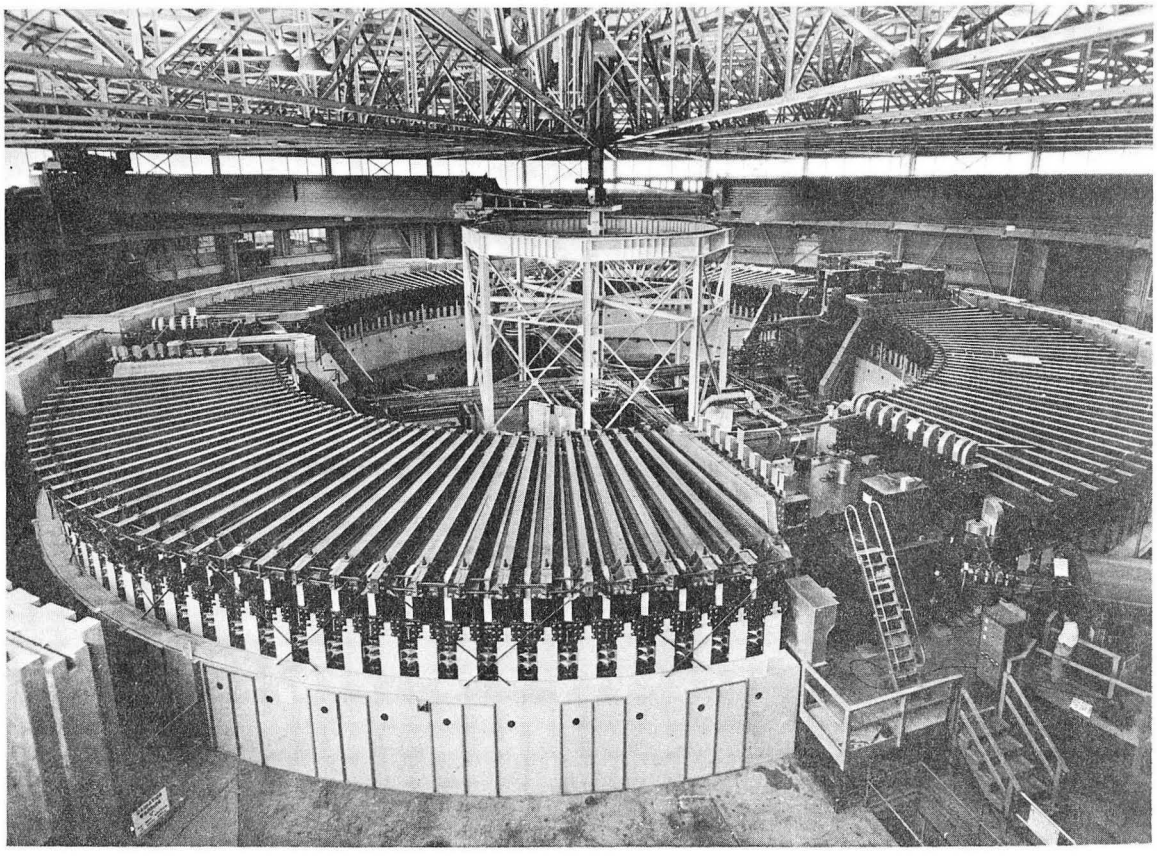
*Work done under auspices of the U. S. Atomic Energy Commission.

function is to control the path of the moving charged particles. Its form is similar to that of a 100-ft-diam. doughnut with a relatively large hole (see Fig. 1). As charged particles are accelerated to higher and higher velocities, a progressively stronger magnetic field is required to hold them in position. One way to attain this steadily increasing field is to pulse the magnet--that is, to start at some low field and then increase it by increasing the current in the windings. Now, a machine the size of this magnet, which at peak field requires 8 400 A and 16 000 V, needs a large power supply. The system that is used for the Bevatron magnet consists of two identical 46 000-kVA generators. In supplying this pulsed power, the generators are subjected to severe cyclic stresses at a rate of 11 cycles/min. This accelerator has been in operation since 1954, and the generator had pulsed 37 488 999 times up to the discovery of a major failure in December 1966.

FATIGUE LIFE GAGE PROGRAM

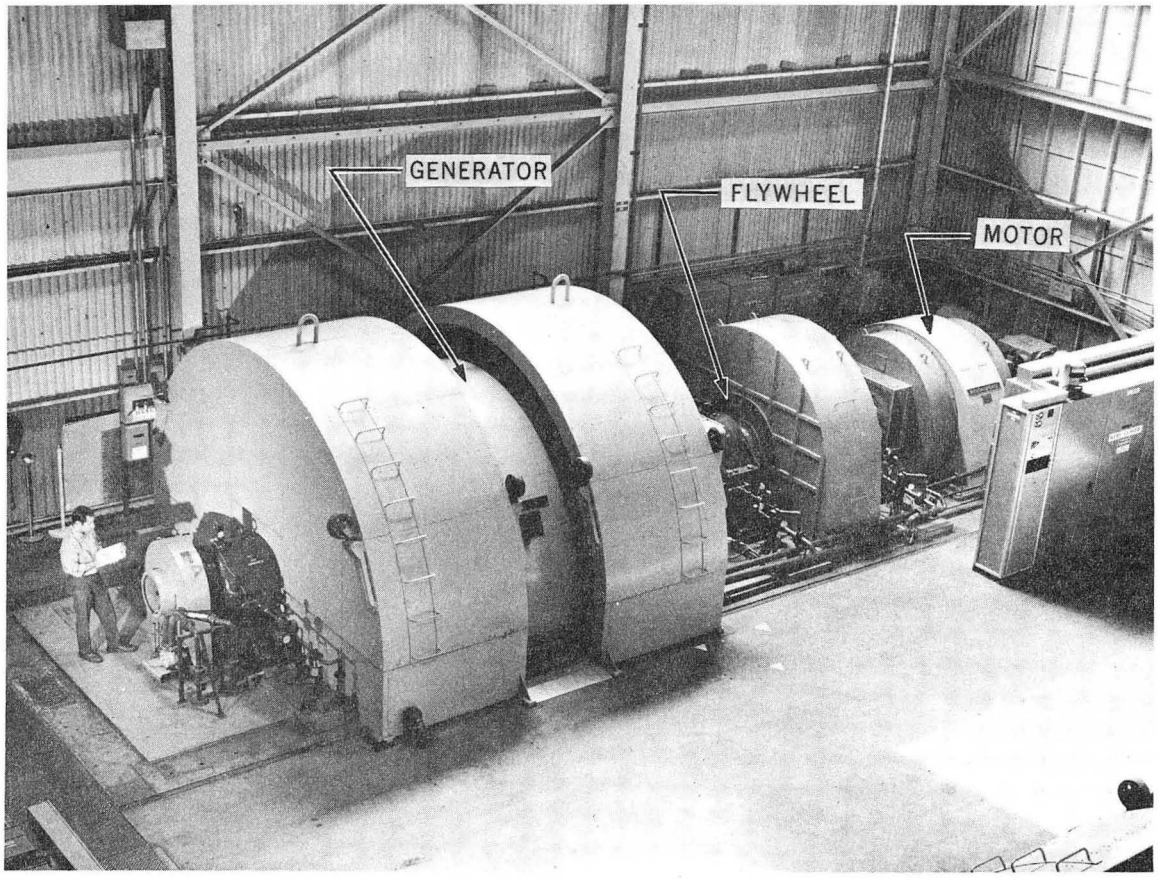
Motor-Generator Description

The two generators, one designated East and one West, sit side by side and are identical: each is driven by a 3 600-hp motor and 67-ton flywheel combination (see Fig. 2). The overall length of the machine is 45 ft, and the total rotating mass is 123 tons. The generator, which is of primary interest in this discussion (shown in Fig. 2 with the sound-suppression shrouds in place), contains eight poles, each anchored to the shaft by two dovetails, which run the length of the armature. Each pole, weighing 6 000 lb, is a copper-coil and steel-core assembly. The 6-ft-long core consists of 1152 1/16-in.-thick laminations stacked and



Bev 1055-A

Fig. 1. Overall view of Bevatron.



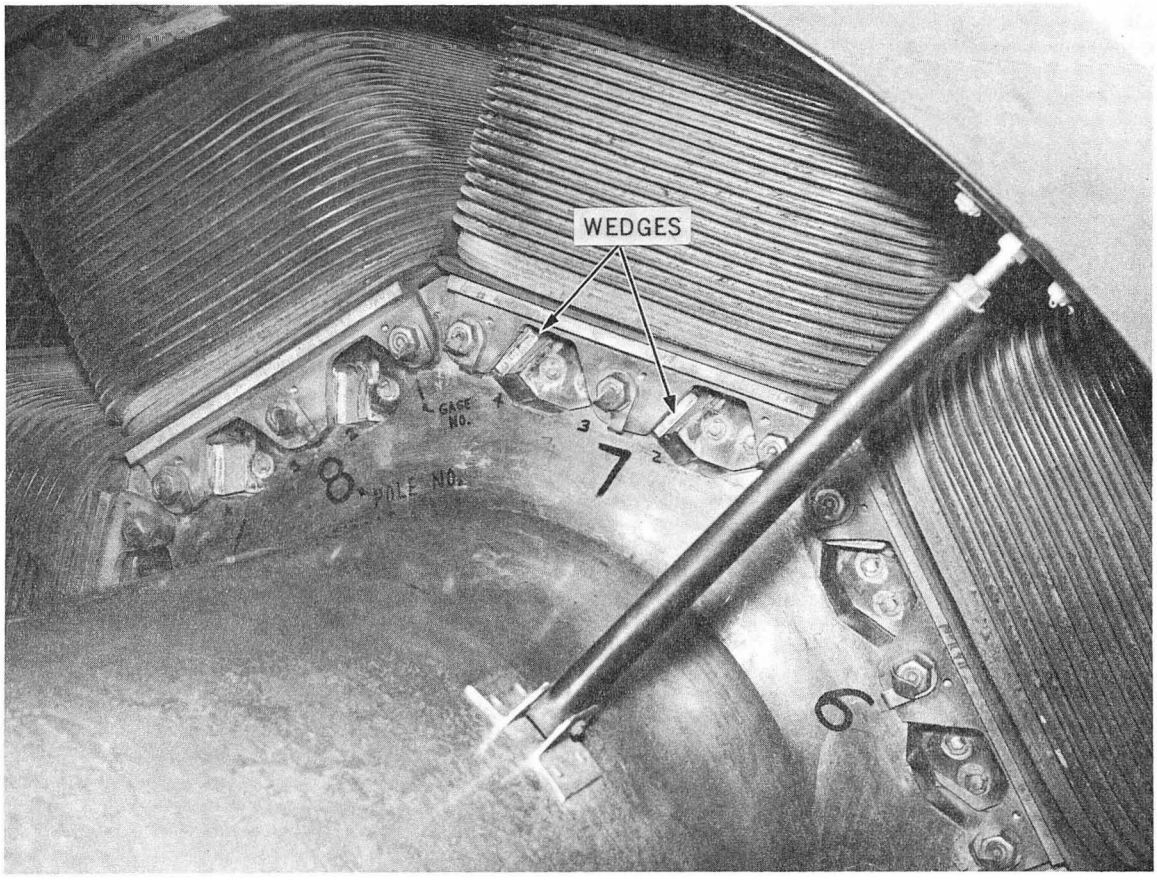
XBB 678-5088-A

Fig. 2. Overall view of motor-generator set.

bolted together. Two wedges, each slightly longer than 6 ft, are driven (one from each end) into a gap between each dovetail and its slot, thereby serving to tighten the dovetails in their slots (see Fig. 3). The total rotating mass of the generator armature shaft and its eight poles is 50 tons, and the pole envelope diameter is 6 ft. Rotational speed at minimum load conditions is 875 rpm, which produces centrifugal loading at the dovetail area of approximately 450 g's. At the end of a pulse the speed has dropped to 775 rpm. The various forces acting on the dovetail part of the pole come from many sources. The obvious source, of course, is the centrifugal force, tending to throw the pole outward and stretch the neck of the dovetail. Another force comes from a portion of the pole coil that overhangs the lamination stack. The centrifugal force of this overhung load puts a tensile stress in the end laminations. Other stresses come from the compressive loads due to driving the wedges. All these combine to give a highly complicated stress field. Calculations indicate that the theoretical total combined stress at the wedge corner is 32 200 psi, with a cyclic stress of plus and minus 10 000 psi.

Generator Failure

During one of the weekly 8-hr shutdowns, a technician inspecting the generators noticed a misalignment. He felt the space between the rotor and stator windings with his hand and noticed that the air gap was unusually narrow. He then compared it with the air gap on adjacent poles and realized that the suspicious pole was definitely closer to the stator than it should be. Upon further investigation, he noticed some parts



XBB 688-5090-A

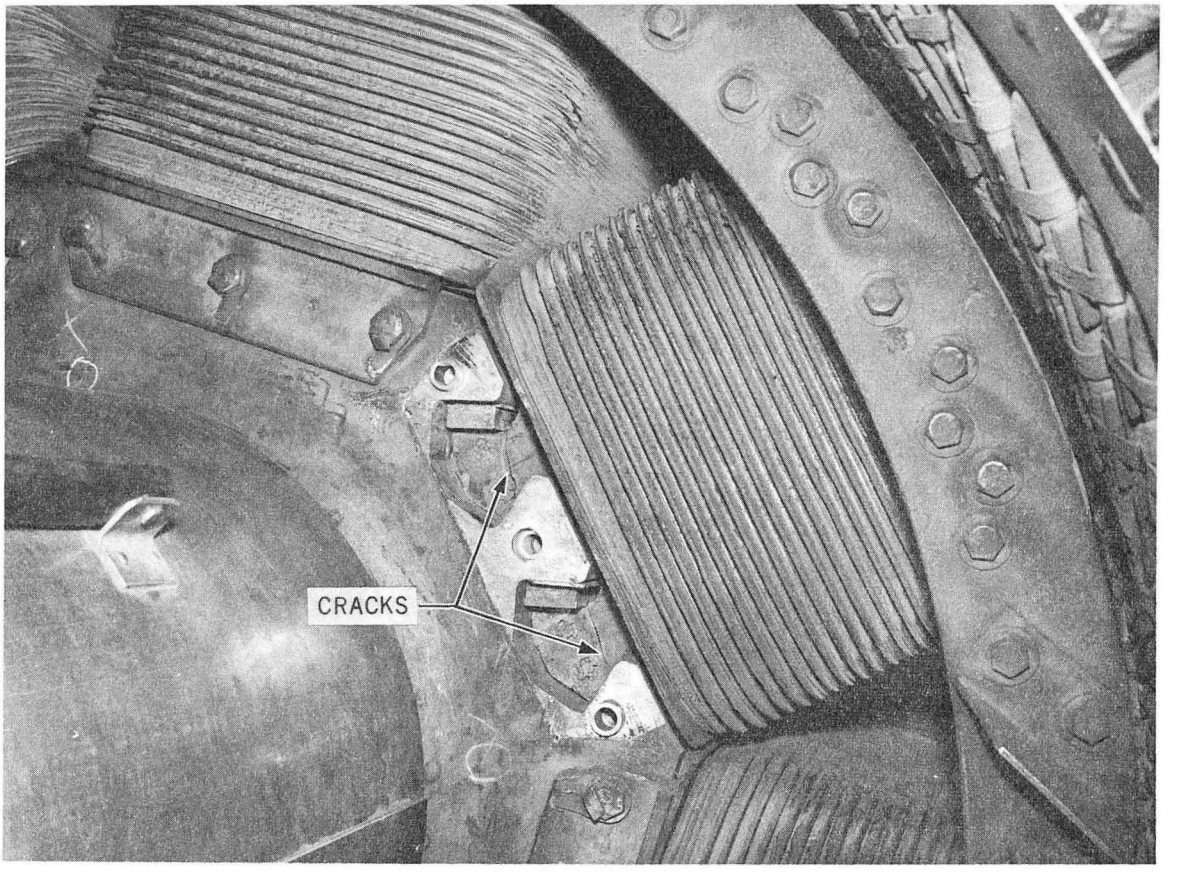
Fig. 3. Generator poles.

were bent.

Steel plates covered dovetails on all poles, preventing visual inspection. It was decided to remove the plate covering the dovetails on the pole in question to see if anything could be learned. When the plate was removed it was obvious why the pole was out of position (see Fig. 4): greeting us were cracks in both dovetails, which at the time looked like the Grand Canyon. The one on the left in Fig. 4 is approximately 0.25 in. wide. It was then decided to remove all the plates covering the dovetails on both machines. The results of the inspection were quite shocking. There were cracks, some entirely across the dovetail neck, on approximately half the dovetails. Then and there it was decided that all 16 poles should be replaced. The resulting shutdown took six months and cost $330 000.

When the pole that first attracted our attention was removed, it was found that the crack extended back 72 laminations (see Fig. 5). One sensed that the crack propagation at this point was quite rapid, and it is anybody's guess how long the machine would have continued to run before the pole was scraping the stator. Certainly the useful life in these poles was limited.

In carefully analyzing the conditions and the design and construction of the machine, it seems obvious, on 20-20 hindsight, why the failure occurred. First of all, the laminations are punched, which results in an extremely hard, brittle edge, fully covered with microcracks. So the very process by which the laminations are manufactured fails them initially. In our mode of operation the crack is simply propagated. Also it was felt that driving wedges with a sharp corner bearing on the edge of



Bev 4137-A

Fig. 4. Original dovetail failure.

XBB 671-282-A

Fig. 5. Pole removed.

the laminations introduced a severe stress concentration. I might add that on inspection of the first few poles, it appeared that the cracks started at the point where the corner of the wedge makes contact with the laminations, so the wedges were thought to be causing a highly loaded condition which contributed to the failure. However, this theory was disproved upon total investigation, when we found that approximately half the dovetails failed from the other side, the crack propagating toward the wedge. We definitely felt that these lamination edges should have been ground and polished, at least in the dovetail portions, to remove the hard, brittle layer and to remove the cracks in the surface. This, however, would have added greatly to the cost of the poles. But surface cracks under fatigue conditions mean trouble, as everyone knows. For the benefit of the manufacturer of the MG sets, one must state that the severe duty that these generators experience is very uncommon. This generator design has been universally applied for many, many years and has not caused any trouble under operating conditions of steady speed and load. We required a different application, a more severe duty, and we pointed up a problem that existed under these conditions.

The new poles that we ordered were manufactured identically to the original ones, but the wedges were changed. The sharp corner was replaced by a 3/8-in. radius, and a 1/16-in. steel shim (softer than the wedges) was added--to spread the load, we hoped.

Fatigue-Life Gage Considerations

As the shutdown was nearing its conclusion, I proposed to the motor-generator operations staff that we look into the possibility of using fatigue

life gages on these new poles to monitor possible fatigue damage. At this time I knew very little of the technical details of the S/N gage; however, I had heard about them in a general way at a technical meeting and felt sure that this would be an excellent application for them. It was decided to install two gages on each of both ends of each dovetail, one next to the wedge and the other at the fillet on the other side of the dovetail neck, for a total of 124 gages (not all the 128 locations are accessible). One cannot get results from an S/N gage unless it is installed where the first crack is going to occur. If the crack does not pass under the gage, you are out of luck. We already had one rather realistic test, though, so we knew where future cracks would occur--if, in fact, they were going to occur at all.

One of the problems was that this machine supplies power to a physics facility, and physicists hate to have their experiments held up. They are less concerned about the condition of the generators than they are about conducting their experiments. As a result we knew we could not prolong the major repair shutdown just to install the gages, but would have to install them during the regularly scheduled Monday maintenance shutdown. Meanwhile, the cover plates that had previously obscured the dovetails were modified for complete access to the dovetail area, allowing visual inspection and adequate access for gage installation.

Another problem was the temperature of the armature. During operation heat is produced, raising the temperature to between 125 and 150° F. Because of the large mass--50 tons of copper and steel--this does not cool off very fast during a shutdown. In fact, the temperature is maintained by heaters to eliminate harmful thermal cycling of the

steel shaft. We could count on a slight amount of cooling during the shutdown, but no more than 10°. As a result we were going to have to accept the fact that we would be installing gages on steel that was anywhere between 115 and 140° F. Also, the air temperature in the area where we would be working would be somewhere around 90° F.

It was decided that BR 610 cement would be the best choice, for two reasons: it is easy to work with and is better for a long-term test. As stated in the introduction, these machines had been in operation for 12 years (1954 to 1966) and had pulsed 37 488 999 times up to the time of failure. There was greater severity in the duty in the 4 years prior to failure (15 000 000 pulses' worth) than in the first 8 years, and this mode of operation was thought to be the culprit that led to the failures. Since the new poles were not appreciably different from the originals, we accepted, with some distress, the fact that unless we changed our mode of operation we could expect failures in the new poles to occur approximately 4 years from startup after repairs. We felt that we should have a cement that would hold up at least that long under our conditions.

Another disturbing aspect was that the original lamination steel was similar to C1040 (tests showed a yield strength of approximately 60 000 psi and an ultimate strength of about 82 000 psi), whereas the replacement poles contained laminations similar to C1020 (yield strength roughly 54 000 psi and ultimate strength about 67 000 psi). The nagging question was, "Would this relatively weaker steel last as long as we had hoped?"

We were also not sure that we would have a metallurgical match between the fatigue gage and the steel. A good metallurgical match is necessary if you want to use the gage as a life predictor. I did determine

theoretically, that for this particular replacement steel we did not have a good match at all. Therefore, we could not expect to use this gage as a predictor of fatigue failure, but rather as a crack detector. Consequently, we did not need to make such extremely accurate resistance measurements as we would have if we wanted to use the gage as a life predictor.

I also reasoned that once a crack started at the edge of the lamination and progressed toward the gage, the steel would gradually open up. This divergence would cause the gage element to respond to the higher strain level, which we would see as a resistance change. So it would give us a warning and therefore be somewhat of a predictor that failure was imminent.

We had no firm idea how we were going to acquire data or monitor the resistance of these gages. We felt that we should get the gages on as soon as possible and develop our data-acquisition techniques as we went along. Slip rings for continuous resistance monitoring could not be used for several reasons: the electrical noise problem that close to the heart of the generator would be insurmountable; also the rings would have to be about 3 ft in diameter if they could be used at all. We could not string wires all over the place to some central location on the armature to take readings unless we could "nail" them down securely. We were constantly reminded of the 450 g's we would have to contend with. We were not allowed to spot-weld to the armature for fear of stress concentrations, so we could not weld on restraining "straps" to anchor wires. There were so many unknowns as to exactly why failure occurred in the first place that no one wanted to take a chance on altering the armature

condition by spot welding. I was afraid that if we used gage terminals, the leads between the terminals and the gage turrets might be ripped off by the high g force. We therefore elected to glue the gages down without terminals and build a probe that would make contact with the gage turrets. We purchased an S/N meter to monitor these gage resistances on the routine Monday shutdowns. We had toyed with the idea of using strain-indicator techniques for instrumentation; however, since we would be making measurements with a probe, I felt that the contact resistance variations and nonreproducibility might wipe out any small resistance changes. Since the temperature is not constant from Monday to Monday, there would be resistance fluctuations due just to temperature changes.

We were worried, further, that we would have a high-cycle, low-strain failure condition and our resistance-change ΔR would be quite small. But again, I reasoned that once the crack started toward the gage, the resistance change would be great enough to read with the S/N meter.

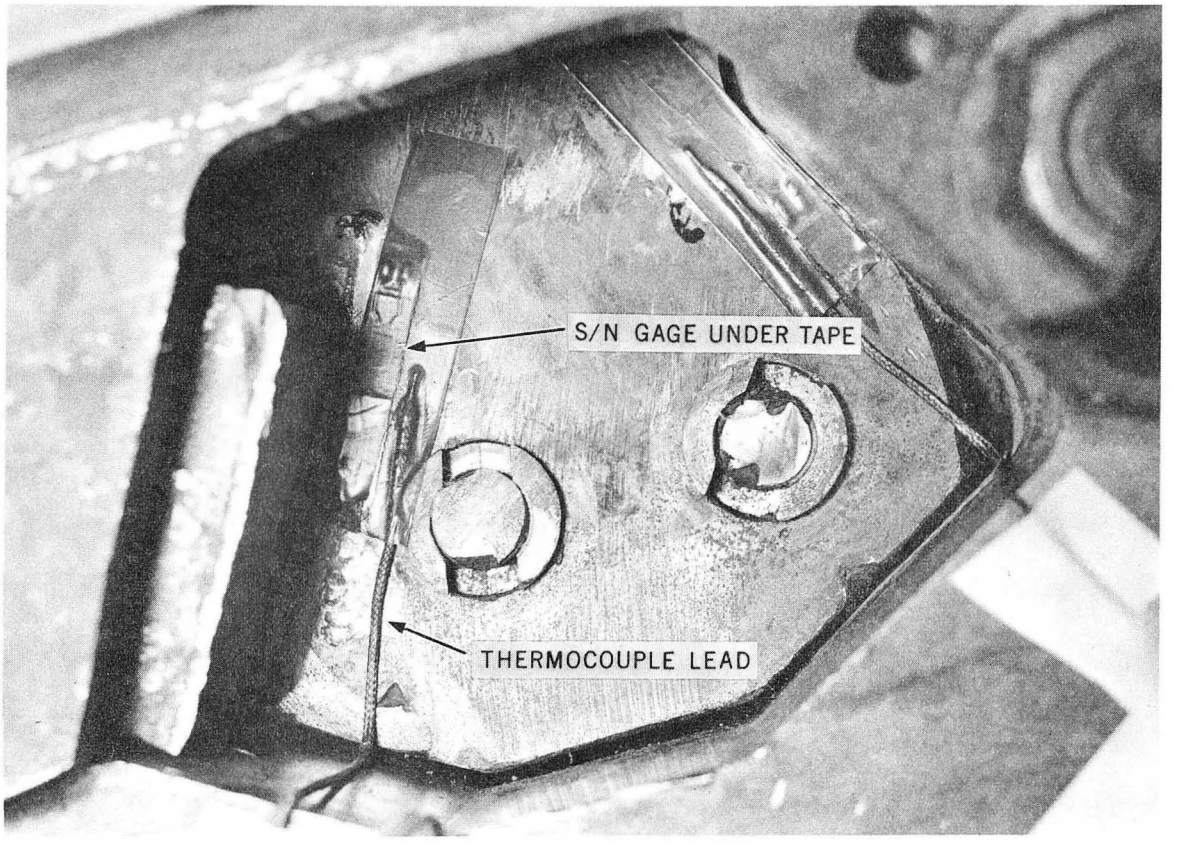
After about 60 gages had been installed, we discovered that the mere act of pushing down on the turrets with the probe to take a reading gradually mashed down the turrets below the surface of the gage encapsulation. We had to install terminals after all. Now, of course, we had to do it in place, but it turned out not to be too much trouble, after all. We presoldered leads to the terminals, bonded the terminals to the 115-140° steel with EPY-150 cement, and after the cement cured, soldered the leads to the gages. The gage and leads were then coated with Gage Kote 4 to encapsulate the leads and keep them from shaking off. Two improvements resulted: our data acquisition became much faster because now we were reading off a rather large blob of solder; and our readings became

much more reliable because with the larger contact area we had better reproducibility. We found that we could live with the 450 g's.

Subsequently we pre-prepared the gages by presoldering the terminals to the gages before installation.

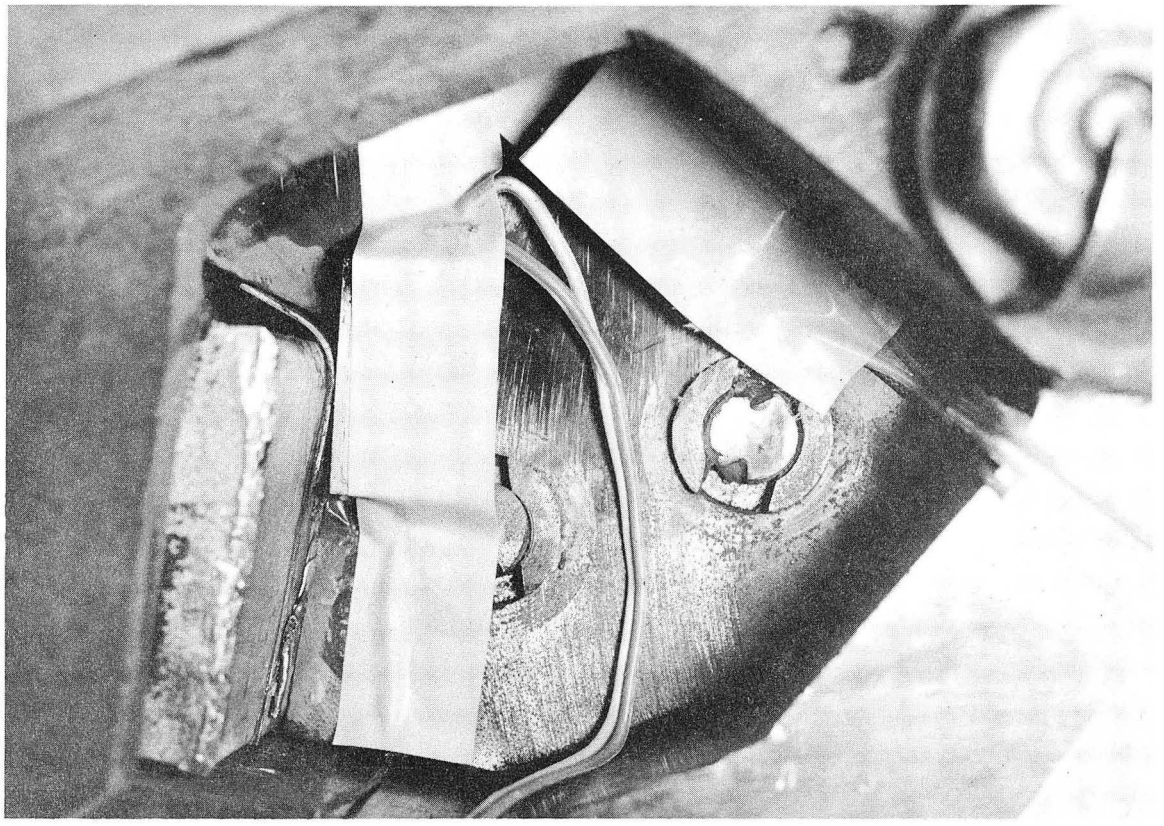
Gage Installation

The laminations were coated during manufacture with a silicate coating that is quite tough, and sanding them by hand would have been quite laborious. We therefore used an S. S. White dental sandblaster to remove this coating in the areas where the gages would be bonded. Over a period of 4 months, the following gage-installation technique was developed. After properly cleaning, sanding metal-conditioning, and neutralizing the steel, Teflon tape was applied and sliced in half with a razor blade (see Fig. 6). One half was lifted up, a thermocouple lead was slipped under it, and attached. Then the other half was lifted up, the steel was coated with cement, the cement-coated gage was placed, and the tape was then pulled down over it. A heater was taped in position (Fig. 7), and a clamping fixture was installed (Fig. 8). The fixture was tightly wedged in the dovetail slot by a threaded strut, which can be seen in Fig. 9. The gage was cured at 275° F for two hours, which is 25° higher than recommended;[1] however, because of possible inaccuracies in our thermocouples we decided to give ourselves this margin of safety. The temperature of each gage was monitored closely until the cure temperature was reached and then periodically during cure. Each heater was plugged into a Powerstat so that the temperatures could be individually regulated (see Fig. 10). The completed installation is shown in Fig. 11.



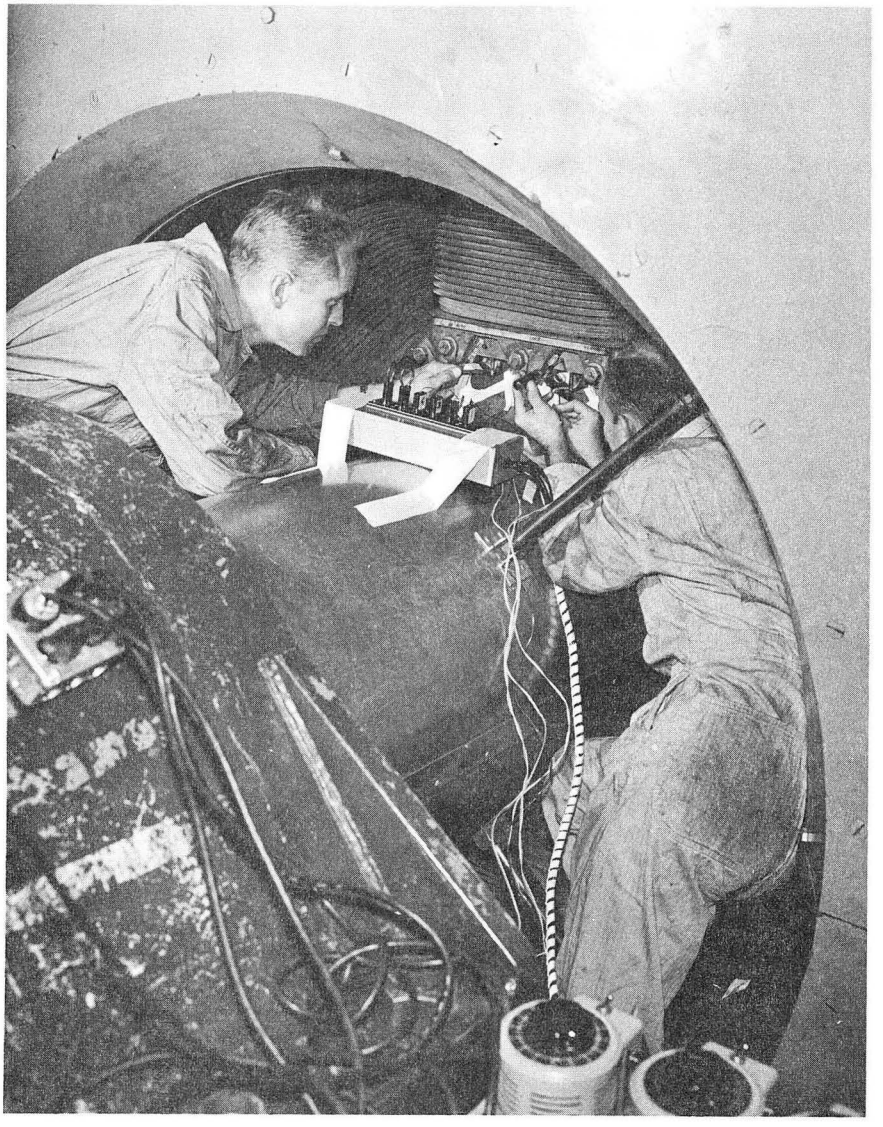
XBB 687-4113-A

Fig. 6. S/N gages and thermocouples in place.



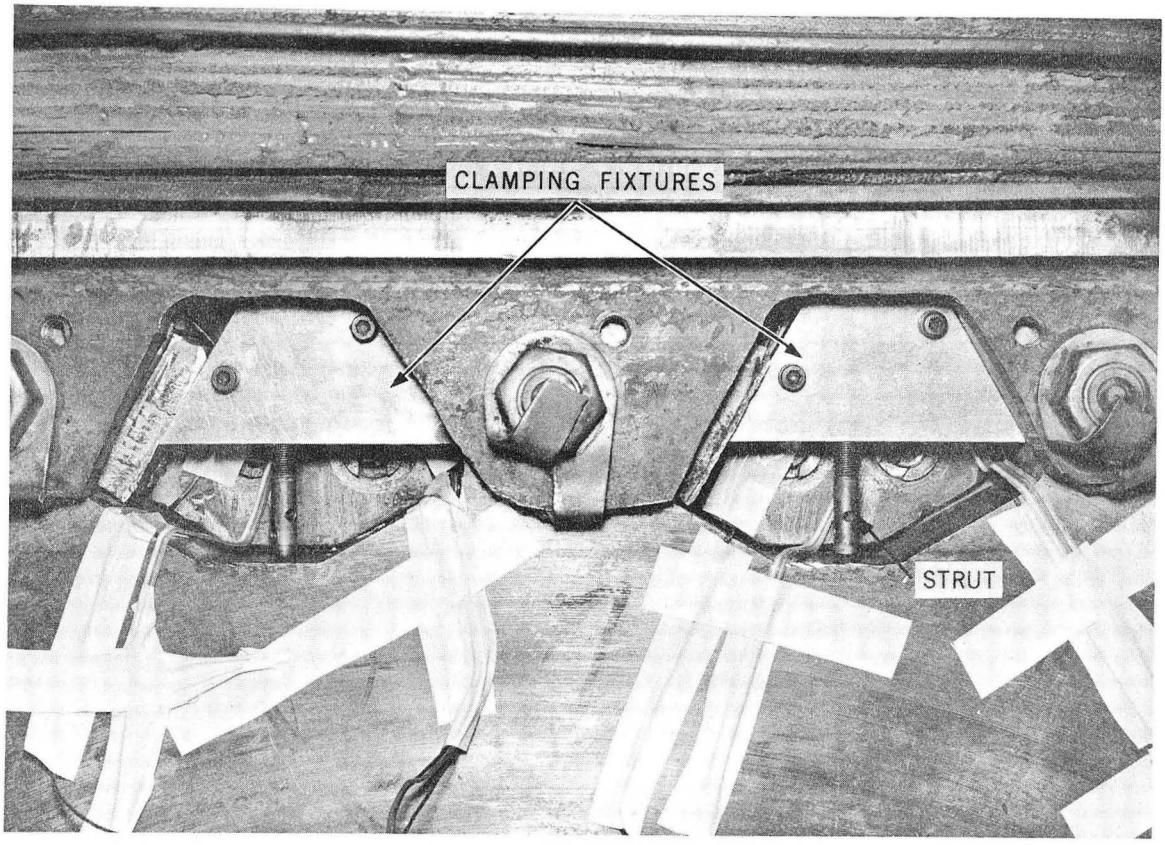
XBB 687-4118-A

Fig. 7. Heaters taped in place.



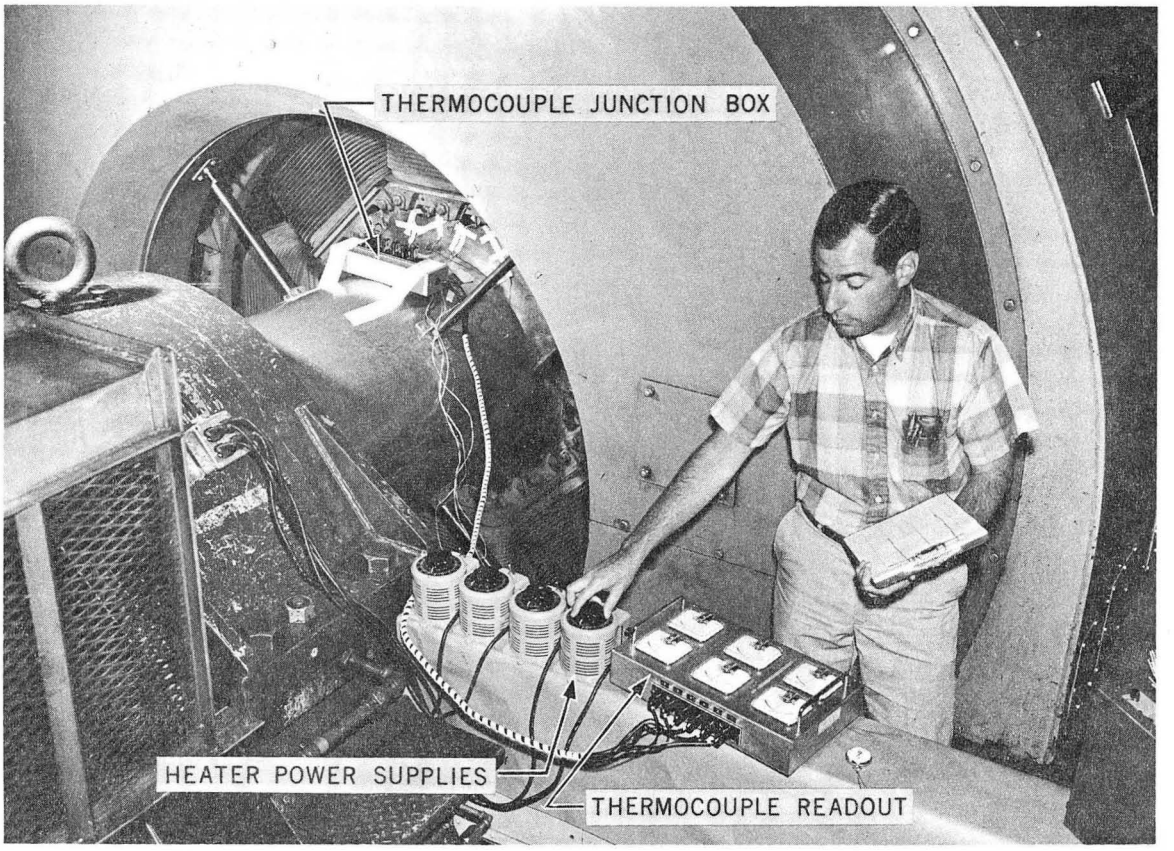
XBB 687-4119-A

Fig. 8. Installing clamping fixtures.



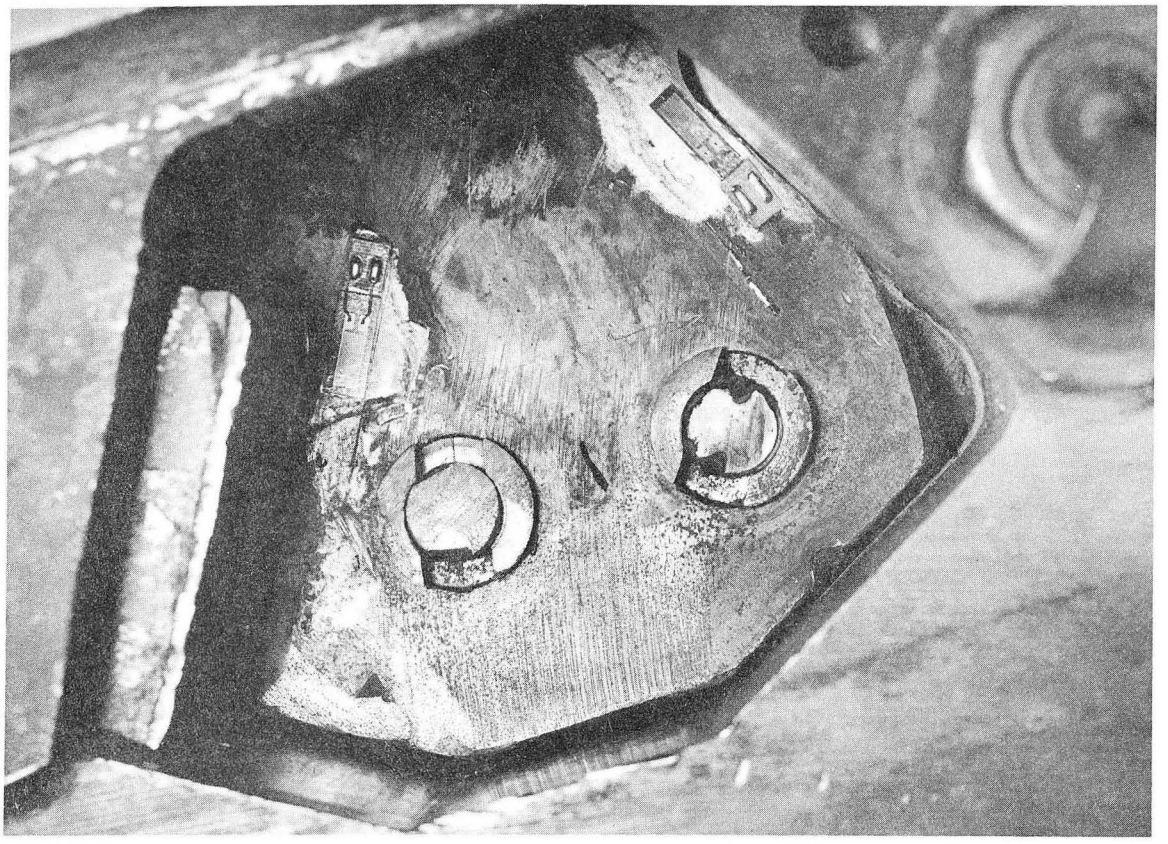
XBB 687-4120-A

Fig. 9. Clamping fixtures in place.



XBB 687-4121-A

Fig. 10. Monitoring cure temperatures.

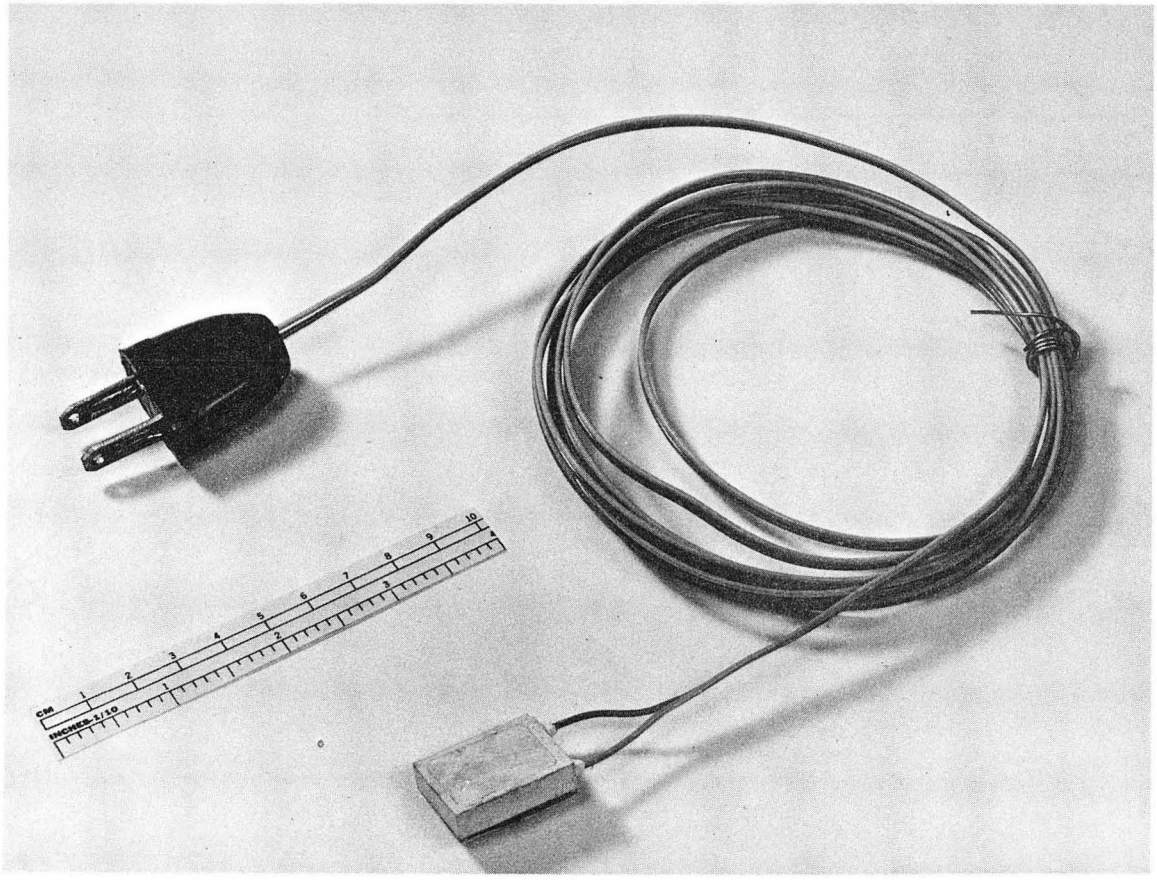


XBB 687-4117-A

Fig. 11. Completed gage installation.

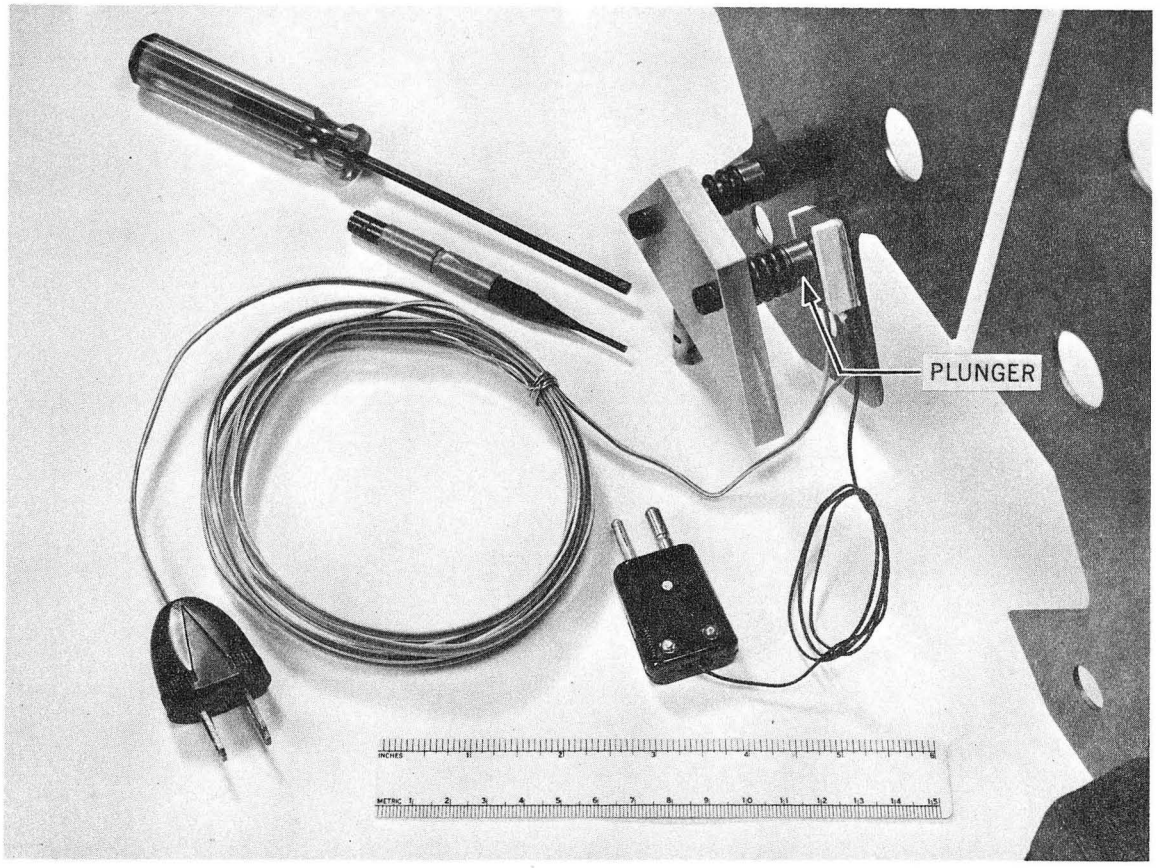
I would like to digress a bit. We feared it would be a fantastic problem to get heat into the cement for curing on this heat sink of 50 tons of steel and copper. We thought it would take a lot of power to bring the gage area up to temperature. However, since we had a laminated structure, we felt that if we could get a highly localized heat source in intimate contact with the gage, we might be able to hold the temperature. After trying several heating methods, we ended up with a ceramic heater that we made ourselves (Fig. 12)--a ceramic body with a 115-ohm nichrome wire heating element inside. We covered the side that contacts the lamination with a layer of ceramic cloth, approximately 1/16 in. thick. This provided a pressure pad, and we found it conformed very nicely to the gage. The ceramic cloth had to be replaced after each gage installation. Pressure was applied directly on the heater body by a spring-loaded plunger in the clamping fixture. (See Fig. 13 for installation simulation.) We found that the plunger also had to have a layer of ceramic cloth to help spread the load and avoid cracking the heater. It was possible to bring the steel up to 275° F in 5 minutes: these heaters put out approximately 60 W at 70 V. We used a slower heating rate than that, however, and brought it up to temperature in 20 to 30 min. The heater body temperature at 70 V is approximately 800° F. The common-garden-variety springs we were using at first were annealed by this high heat. We then had springs made of Inconel X, which worked perfectly.

We found that with two men working, one on each side of the shaft, we could install four gages (two per dovetail) in one maintenance period. This also allowed some time for taking resistance readings of the gages



XBB 678-5034-A

Fig. 12. Heater



XBB 678-5198-A

Fig. 13. Gage installation simulation.

we had put on previously. Some dovetails are quite rough; the steel has gouges and scratches in it. Several times we had been hesitant to even attempt to put a gage on the surface. However, we found that if the groove or gouge is not more than 0.010 to 0.015 in. deep, the gage works satisfactorily. The edges of the groove must be sanded smooth, however. The ceramic cloth pressure pad will then push the gage down into the groove, accomplishing a good bond. On the other hand, a scratch can be bridged satisfactorily.

New Cracks Appear

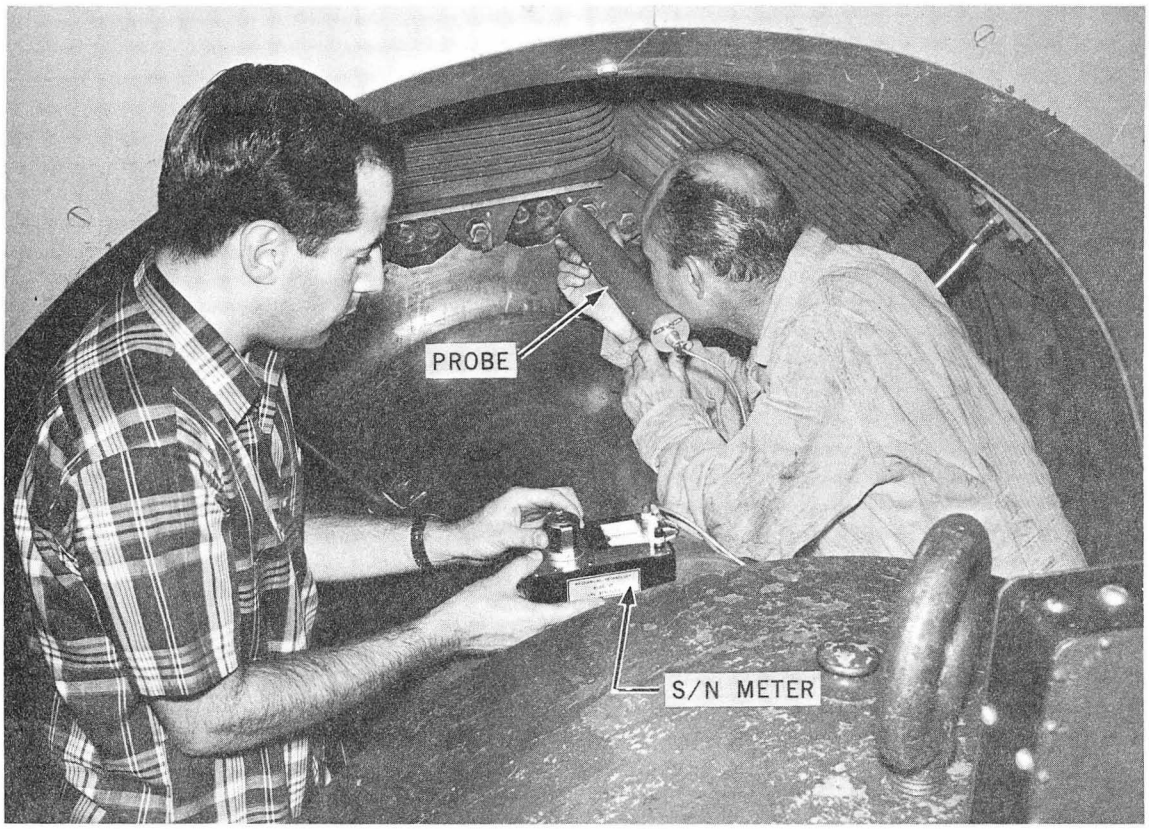
We started installing gages in June of 1967 and everything went along quite smoothly. Then interesting things started to happen. On October 30, 1967, only 4 months after startup, in trying to measure the resistance of one particular gage on the West machine, gage WS 7-4, we could not get a closed circuit. (See footnote "a" in Table I for gage position code; also refer back to Fig. 3.) We inspected the gage closely with a magnifying glass and found that, sure enough, there was a crack through the first strand of the gage. The dramatic thing about the performance of this gage is that on general inspection you would never see the crack unless you knew one was there and were carefully looking for it. When the backing of the gage cracks, you can see its crack much more clearly than you can in the steel itself.

I had mixed emotions about this first crack. All along I had had visions of putting all these gages on and never finding out whether or not they would spot cracks; in other words, there might not be any new cracks. So when we did finally have this first crack, I was quite happy to see that

the gage acted as it was supposed to and that we had installed the gages in the right place. However, I was sorry to see that the problem was still with us.

Panic ensued in the motor-generator room. Could it be that instead of 4 years' life, we had only 4 months' life in the new poles? The gage was removed--rather brutally--and a 3/32-in.-diam. hole was drilled at the end of the crack in an attempt to stop propagation. We then put on a new gage next to the stop-drill hole, which penetrated only the first lamination. Then, on December 18, 1967, while trying to measure the resistance of one of the gages on the East machine, ES 7-2, we kept getting an open circuit. Upon closer inspection, we found we had a repeat performance. There was a very fine hairline crack through the first strand of the gage. That gage was also removed, a 3/32-in.-diam. stop-drill hole put in the first lamination, and a new gage installed next to the hole. We had no further trouble with this crack.

When that first crack after startup appeared in the West machine back in October 1967, we were caught unprepared. We had not formulated a data-acquisition procedure, and we were still working on various probe designs. While we had a crude probe and had taken some measurements, we did not notice a resistance change previous to seeing this crack and, in fact, we had not taken readings for several weeks prior to its appearance. For the second one, on the east machine, we were better prepared. We had developed a probe that worked very well (see Fig. 14). It has built-in, battery-powered lights that illuminate the gage. On the probe tip are two contacts of annealed 0.003-in.-thick by 1/16-in.-wide platinum. These contacts are spaced to match the spacing of the gage terminals.



XBB 682-570-A

Fig. 14. Gage resistance readout.

To looking back at the resistance data sheets, though, we found that 3 weeks had elapsed between our last reading (we were not allowed access to the machine) and the subsequent crack in the gage. From the last data taken, we noticed that the resistance of gage ES 7-2 had increased from 100.38 to 101.60 ohms, a 1.22-ohm increase. Once an increase in resistance is noted, we would have to read the gage frequently during the week in order to see the gradual resistance change, denoting the progress of the crack. Pulses are accumulated at about 100 000 per week, and once the crack starts, it grows rapidly. By waiting 1 week to take the next reading, we would possibly miss the exact moment of failure. (See Table I for a summary of crack information in the new dovetails.)

Faced with what now seemed to be a reappearance of cracks, we asked ourselves, "What do we do now?" We could keep running, watch the cracks grow, hope that they did not propagate too fast, and maybe get the 4 years' life that we had predicted. Or we could shut down operation and make repairs right then and there. Well, it's a pretty difficult decision to make, especially when you know there will be experimenters anxious to continue their experiments. On the other hand, when you consider that these are but hairline cracks, maybe 1/8 in. long, you realize that possibly there is no real danger yet. The big question is how fast will the cracks develop and progress, and in how many laminations behind that first one are there others. Because of the way the poles are manufactured--simply punched and not dressed down in any way--the edges of the laminations are not all in the same plane when assembled, so they do not all bear equally on the wedge. There is

TABLE 1

FATIGUE LIFE GAGE SUMMARY OF NEW DOVETAIL FAILURES

Gage position on generator	Date first resistance change noted	Total ΔR just before first gage failure (ohms)	Date first gage failure	Total cycles to first gage failure	Total cycles first gage saw	Stop-drilled	Regaged	Date second resistance change noted	Total ΔR just before second gage failure (ohms)	Date second gage failure	Total cycles to second gage failure	Total cycles second gage saw
WS 7-4[a]	Missed it	—	Oct.30, 1967	1,573,966	1,573,966	Oct.30,1967	Nov. 6,1967	Jan.15,1968	0.14	Jan.29,1968	2,641,658	971,190[b]
ES 7-2	Nov 27, 1967	1.22	Dec.18,1967	2,208,873	889,617	Dec.18,1967	Jan. 2,1968	No further problems				
WS 7-2	Jan. 8, 1968	2.58	Feb. 8, 1968	2,741,404	2,741,404	Feb.26,1968	Feb.26,1968	No further problems				
WN 6-4	Missed it	—	Apr.19,1968	3,598,383	143,193	Apr.29,1968	Not regaged[c]					

[a]Gage position code.

WS 7-4

West generator — Gage 4, same numbering system as on poles.

South end — Pole 7, numbered clockwise for S end, counter-clockwise for N end.

[b]Continued drilling in first and second laminations to locate end of crack and succeeded in stopping propagation.

[c]Drilled down to the tenth lamination and succeeded in stopping propagation.

XBL6884905

the possibility that the end lamination, which is the only one you can see, is not making good contact and is not carrying its share of the load. Therefore, a small crack in this possibly lightly loaded lamination may mask a very severe cracking situation in heavier loaded laminations further in. But then you can rationalize that because of the nature of the loading, the lamination or laminations at the end have to be the ones to crack first.

The decision was to keep running. Needless to say, we watched resistances very carefully.

Having developed our resistance-monitoring techniques, we found that with the S/N meter we could resolve 0.01 ohm without too much trouble. We clean the terminals with pure ethyl alcohol before reading to try to minimize contact resistance problems. Our contact resistance variations from reading to reading are about 0.05 ohm maximum.

For the first year and a half, from June 1967 to December 1968, we took resistance measurements and pole temperature readings once a week. After December 1968 we changed to monthly readings (for reasons I will explain later). We found that the temperature fluctuated between 105° and 130° F in successive weeks. We also noticed that there were changes in resistances, again less than 0.05 ohms, with and without temperature variations. If we got a reading that was 0.10 ohm higher than the previous week's, we flagged it. If the next week's was no higher, we were not too concerned, but we continued to observe it for a while. If it returned to the original value, we tended to forget about it. We also watched for steadily increasing resistances over several weeks.

On January 8, 1968, we noticed that the resistance of the gage in position WS 7-2 increased 0.13 ohm. Then on January 15 there was an additional 0.03-ohm increase. At the time, this additional but now small increase in itself seemed to indicate to us that the gage had settled down. (Contact resistance variations might cause a change that small.) Also on January 15 we noticed a 0.14-ohm increase in gage WS 7-4 the replacement for a gage that had previously cracked. On January 29, two weeks later, WS 7-4 failed. We suspected that this new crack in WS 7-4 was a continuation of the original failure. We probably had not removed all of the original crack, and it was propagating again. Now, it turns out that watching the crack propagate from grid strand to grid strand is an excellent way of keeping track of the crack progress, so we decided to leave this gage on and watch it for a time.

We noticed on January 29 that gage WS 7-2 had increased an additional 2.42 ohms. Upon close examination of the gage and surrounding area, we noticed a very fine crack approximately 1/64 in. long just starting at the edge of the lamination and heading straight for the gage. The texture of the gage grid looked suspicious (discolored and very grainy), but no crack could be seen in the gage. Obviously our attention was now intensely focused on gage WS 7-2. We knew that a crack was imminent. Sure enough, the next week, on February 5, the gage failed. Meanwhile, the crack in WS 7-4 continued to lengthen. We decided to watch the situation for one more week.

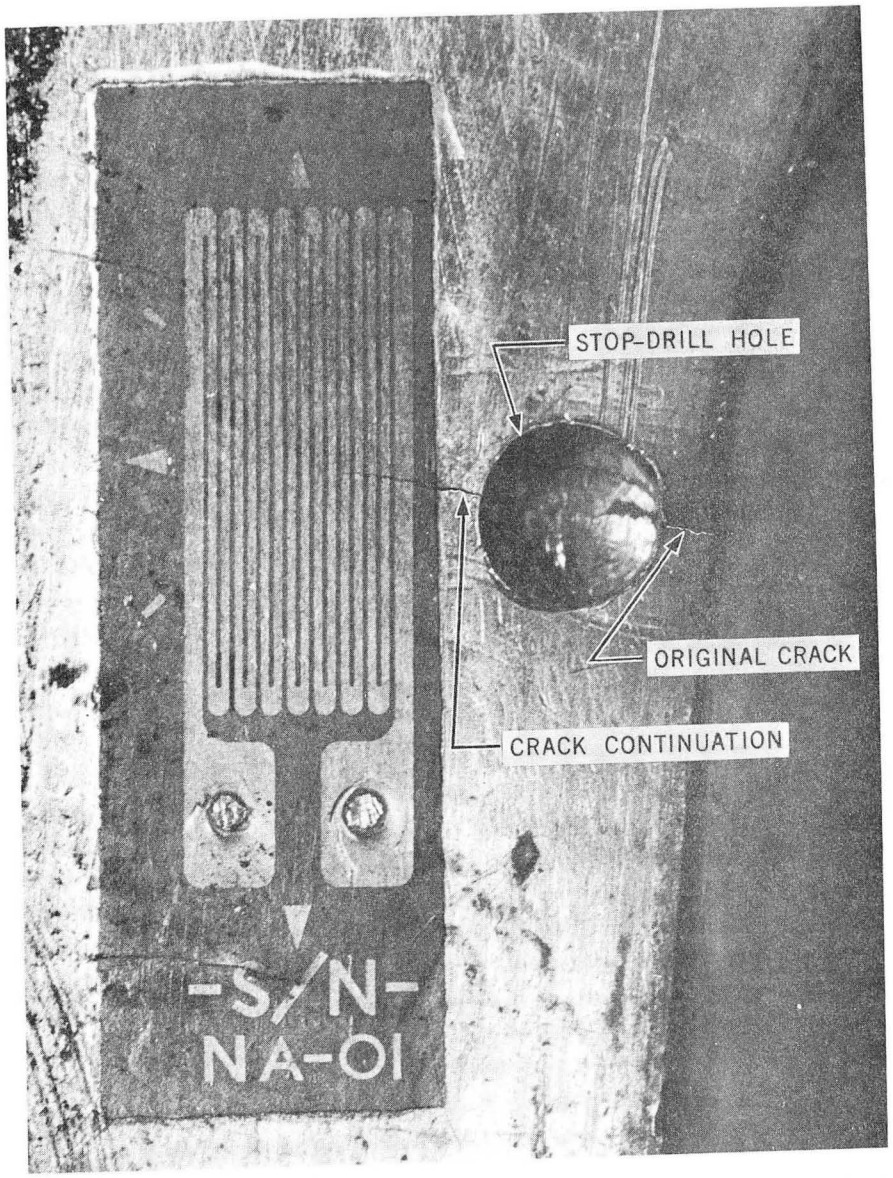
On this same date, February 5, we started taking weekly photographs of the cracks. We found that with the good photographic techniques that we had to develop for this job we could see the cracks and keep track of

their progress much better by analyzing photo enlargements than we could with the naked eye. The important role that photography can play in this type of application cannot be too strongly emphasized.

Figure 15 shows the original crack, stop-drill hole, and crack continuation in the second gage in position, WS 7-4. At the bottom of the hole, which is the surface of the second lamination, a crack can be seen approximately halfway across the drilled hole. Upon examining this crack, we suspected that several laminations might be affected. Notice also in Fig. 15 that the gage turrets are mashed from the probe pressure.

The next week, February 13, 1968, gage WS 7-4 was sanded off, never to return. We continued to have problems with this cracks propagating, but after a series of stop-drill holes down to the third lamination, we succeeded in stopping the crack growth. On February 13 gage WS 7-2 was also sanded off. On February 26 we stop-drilled to the second lamination and installed a new gage WS 7-2 (see Fig. 16). We had no further problems in this dovetail.

On April 19 we discovered a crack while taking readings on gage WN 6-4, at the other end of the West machine. Closer examination showed that there was a crack through the entire gage and beyond (see Fig. 17). A check of the installation records showed that this gage had been installed approximately a week and a half earlier. During this week and a half we were unable to obtain resistance readings except for the initial installation resistance, as our S/N meter was out of order. We did make a crude measurement the week before and found that at least there was continuity, so the crack had not yet fractured the gage. The crack was difficult to see because of the many scratches in the

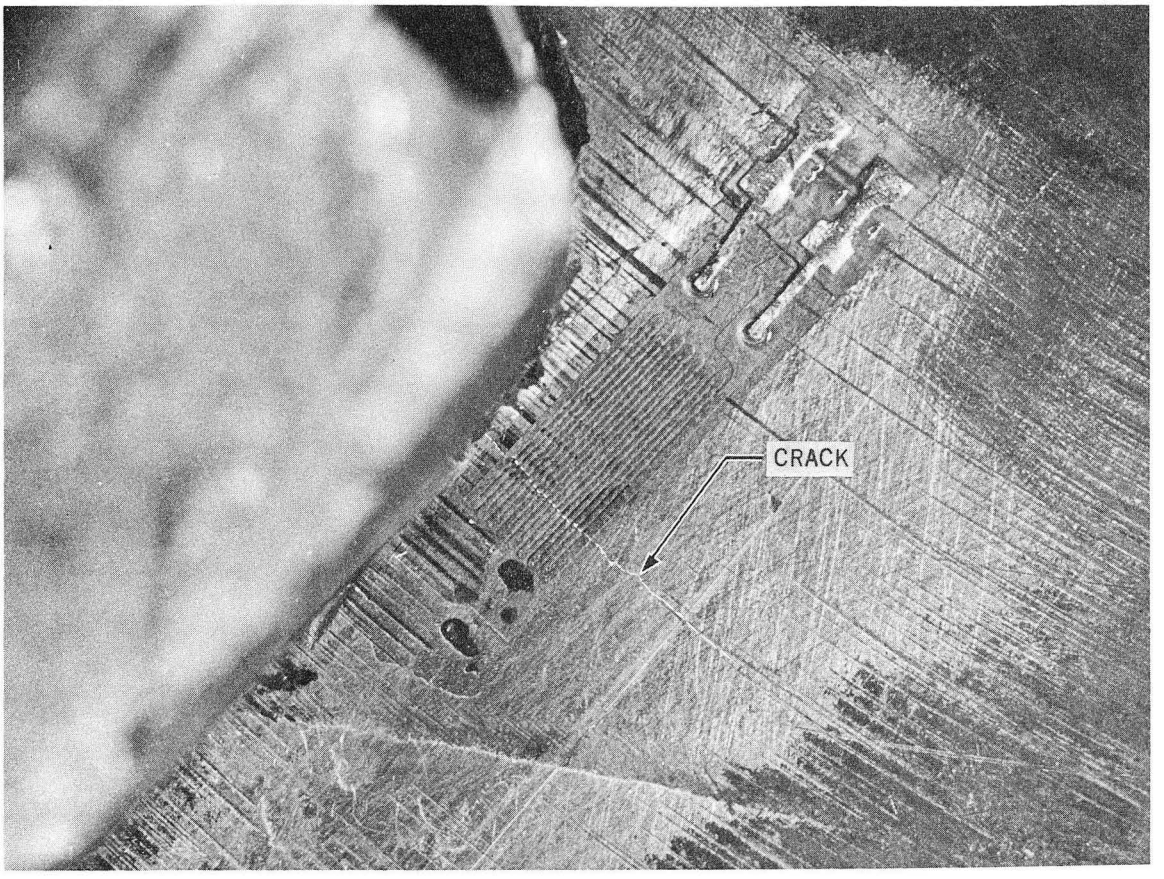


XBB 682-564-A

Fig. 15. Crack continuation at gage WS 7-4.

XBB 683-1440-A

Fig. 16. Stop-drill hole and new gage, WS 7-2.



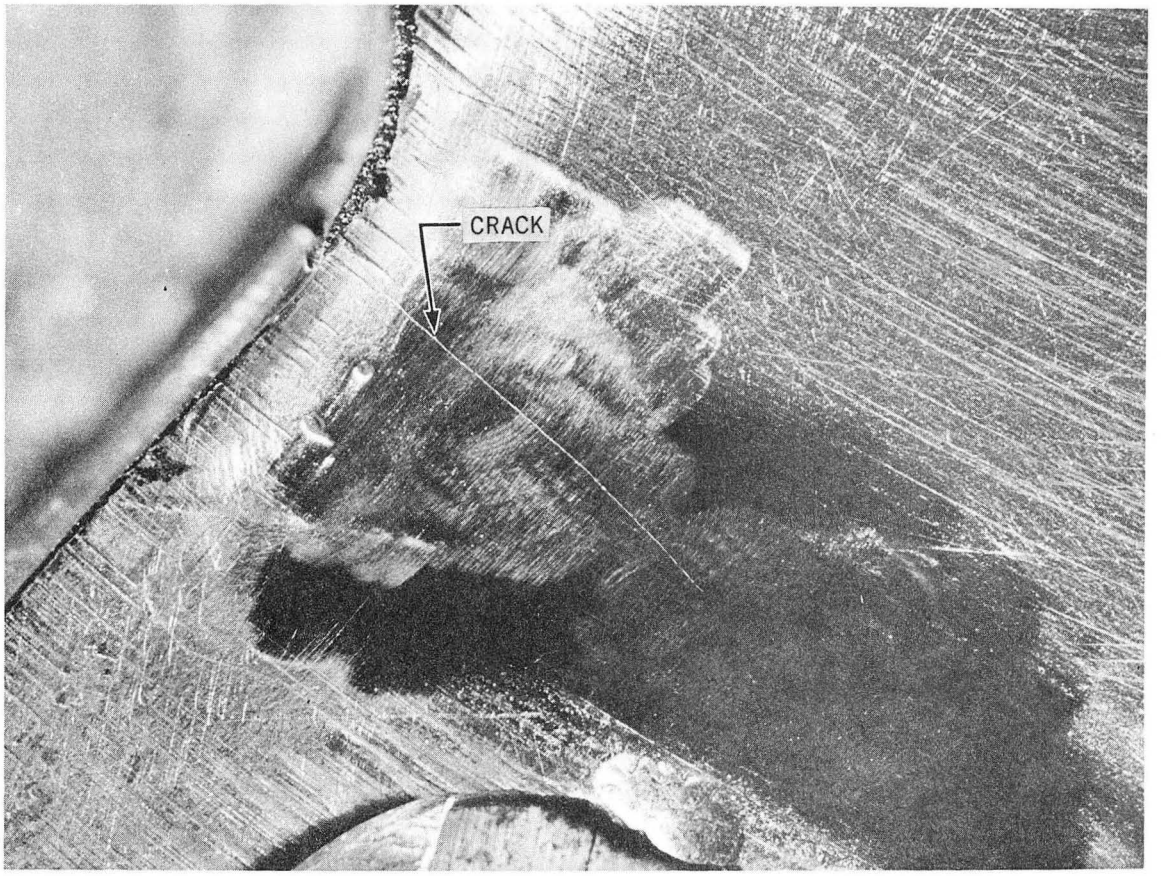
XBB 684-2075-A

Fig. 17. Crack through gage WN 6-4.

lamination surface, and, in fact, the crack was parallel to the direction of the scratches. When the gage was installed there was no noticeable crack, although one may have been present. This gage was then sanded off and the surface ground down to remove the scratches and to determine exactly how long the crack was. Inspection revealed a crack approximately 3/4 in. long (Fig. 18). Stop-drilling revealed cracks in subsequent laminations. We began to get rather apprehensive at this point.

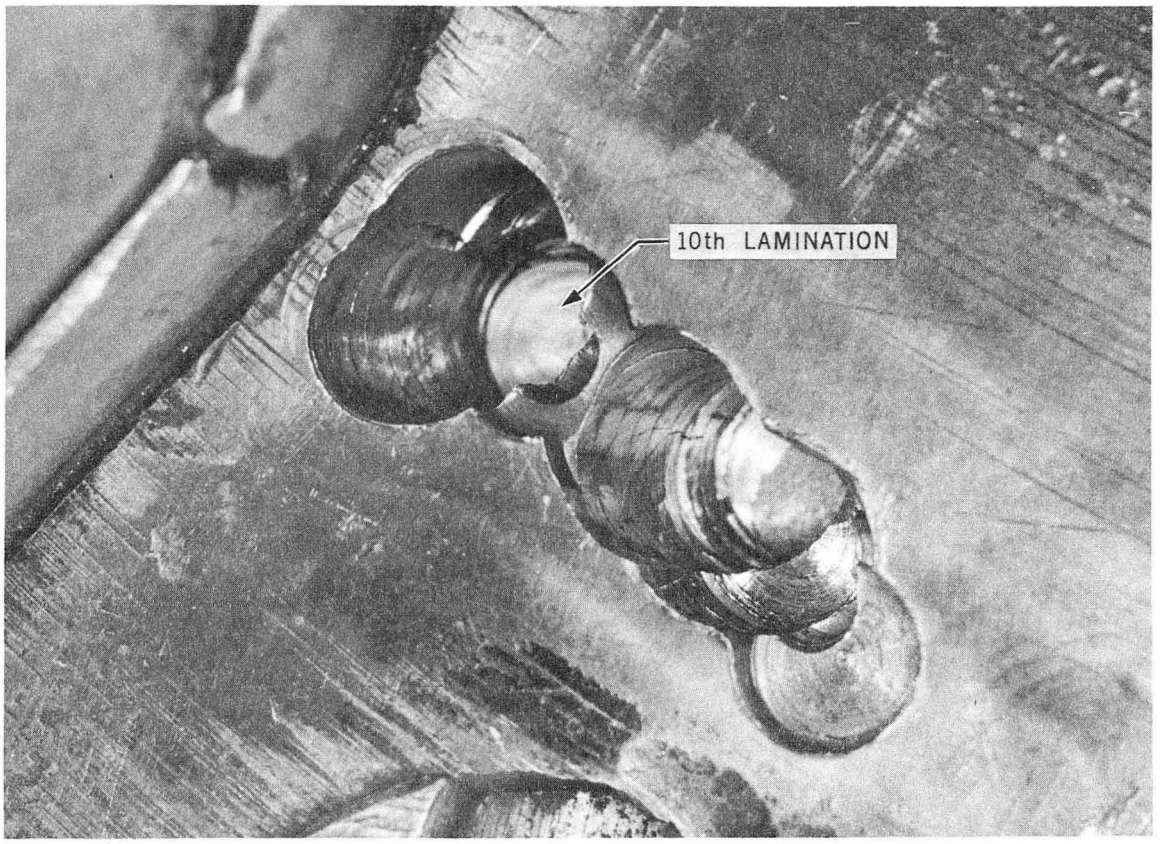
To make a long story short, we wound up with a dovetail looking like a piece of Swiss cheese (Fig. 19), and before we were through we had drilled all the way to the tenth lamination before we found no further evidence of cracking. We felt that had we installed this gage much earlier, we might have seen a resistance change and the appearance of the crack just as it started. If we had stop-drilled then, we probably would have limited the crack to the first lamination. However, we now succeeded in stopping the crack progression. To date things have been relatively peaceful, with no new cracks.

As I mentioned earlier, we started out taking resistance readings and pole temperature measurements every week. In December 1968, approximately 8 months after the appearance of the last lamination crack, we decided to relax our S/N gage vigil somewhat. Since we had no changes in resistance during this 8-month period we decided to take resistance readings only once a month. We stopped taking temperature measurements, as we found that temperature fluctuations did not have a significant effect on gage resistances. Our photographic surveillance was likewise changed to once a month.



XBB 684-2076-A

Fig. 18. Gage WN 6-4 removed.



XBB 687-4136-A

Fig. 19. Stop-drill holes in WN 6-4 area.

By July 1968 we had completed the gage installation at all locations except 16. These last 16 gages (8 per machine) presented a problem in that the dovetails at one end of each of two poles on each generator are covered by steel plates that are used as weights for dynamic balance of the rotor. In addition to the cover plates, weights are inserted into the dovetail slots and rest up against the end lamination of the poles. The presence of cover plates, of course, prevented us from visually inspecting the dovetails underneath, and their removal and reinstallation was a difficult and time-consuming task.

Now, early in the program, we realized that somehow we would have to install gages at these locations and monitor their resistances. But we would have to wait for one of the semiannual 2- or 3-week shutdowns in order to have sufficient time to complete the job all at once. We certainly did not want to foresake the eight dovetails and just hope there would not be any failures at these locations. They represented 13% of the total. We were constantly reminded that the presence of cover plates masked the severe and nearly catastrophic failures in the original poles.

Our opportunity to complete the gage installation came in December 1968 during a 3-week shutdown for changes in the Bevatron experimental setup. We removed the cover plates and slot weights, bonded the gages to the poles in the usual manner, and then mounted additional terminals, with EPY-150, on the armature in an easily accessible spot just below the area occupied by the cover plates. We then connected the gages to the secondary terminals with #27 Soldereze wire, and encapsulated the gages and lead wires with liberal amounts of EPY-150 cement. See

Fig. 20. Figure 21 shows the cover plates in place and the terminals from which the readings are taken. Obviously reading these gages is easier and faster than reading those without the auxiliary terminals, since these terminals (in Fig. 21) are outside the dovetail slot and are more centralized.

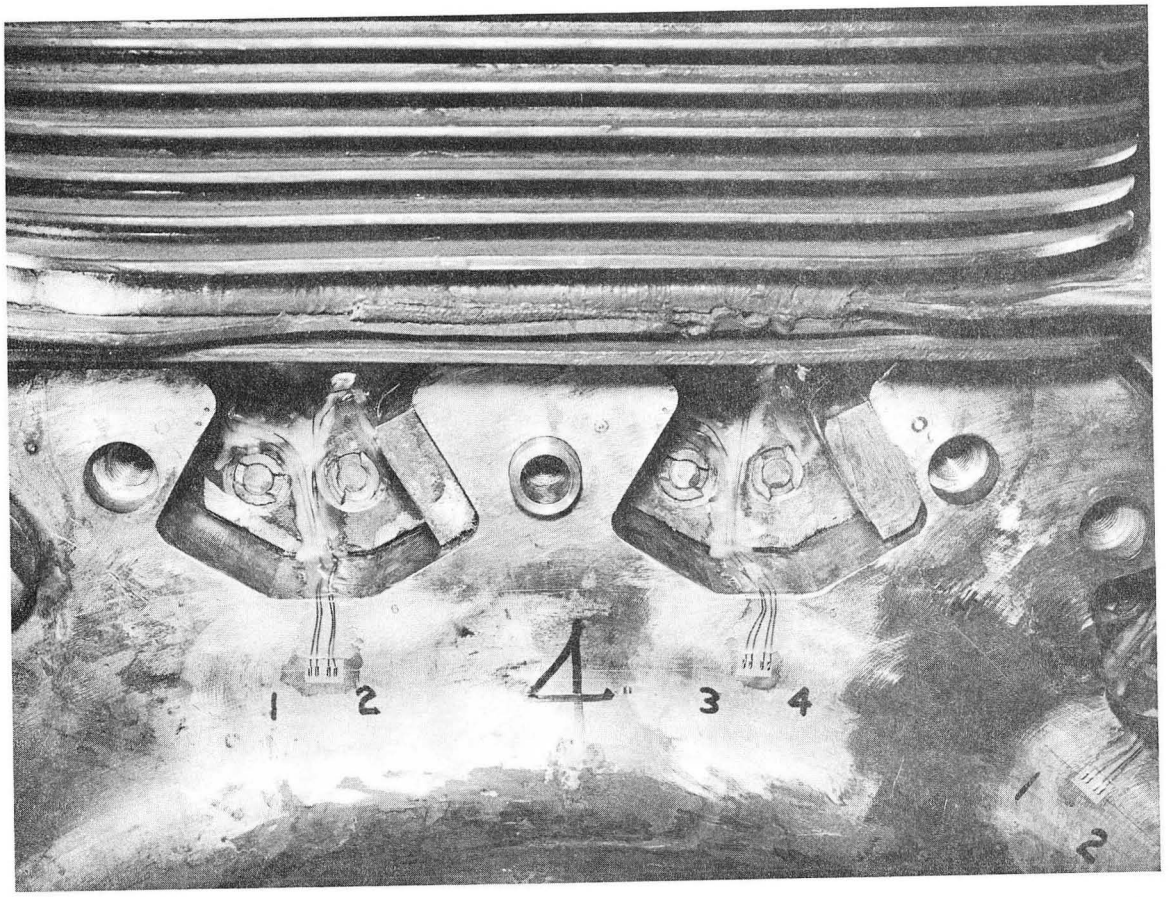
We placed a 1/8-in. rubber pad between the end lamination and the slot weight and between the bottom of the slot and the weight. This would protect the gages and lead wires if the weights should shift.

We had some minor problems with leads coming loose from the gage turrets after anywhere from 8 to 26 months of operation. This happened in seven cases. These were gages that we had obtained without leads (FNA-01) at the start of the S/N gage program. Evidently we did not get a good solder joint at the turrets when we installed the leads and they were shaken loose in operation. We had no difficulty repairing them in place, however.

We have had no trouble with the gages that we obtained with encapsulated leads, the FWA-01 gages. The last 30 gages that we installed were of this type. We strongly recommend using the gages with encapsulated leads whenever possible for two reasons: they are cheaper in the long run because you don't have to fool with soldering on the leads yourself, and the integrity of the factory-attached and -encapsulated leads is much more certain, especially in this kind of service.

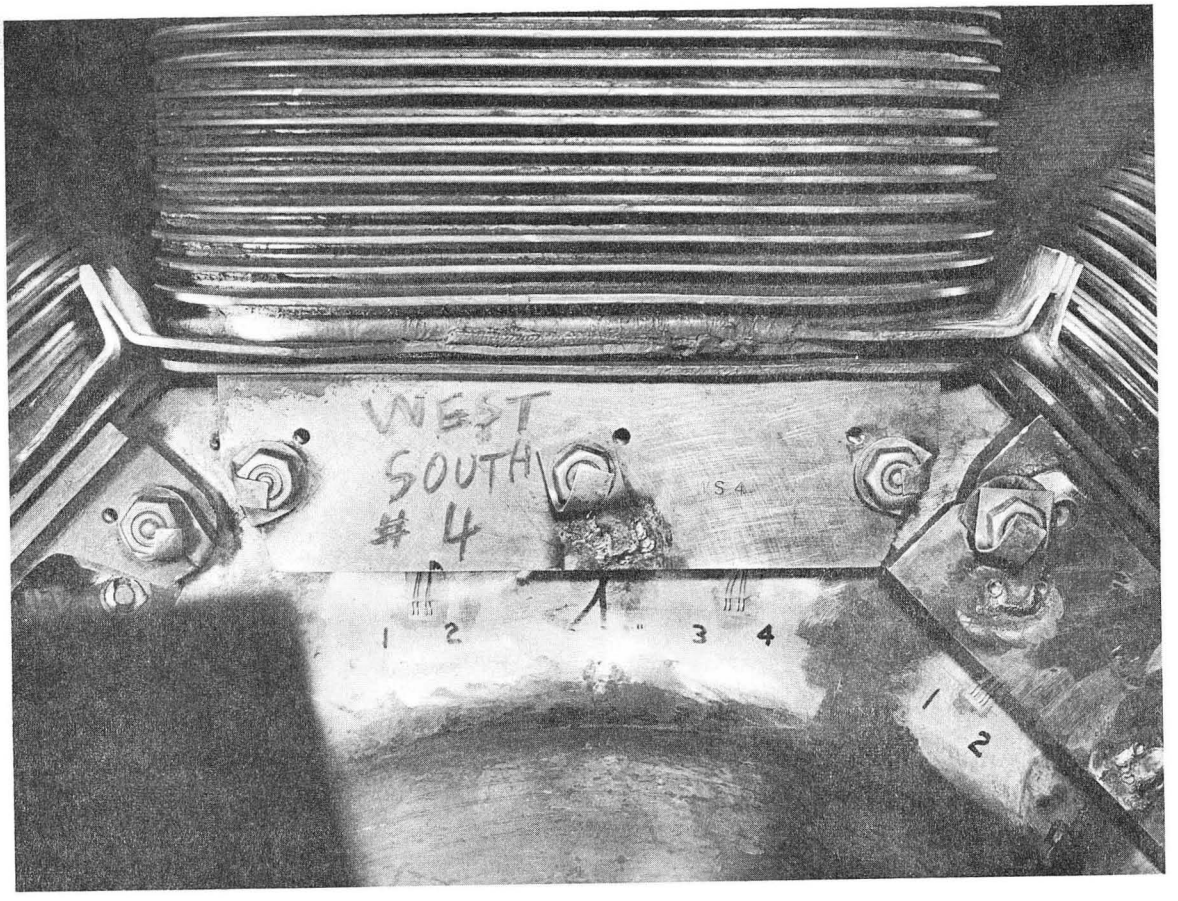
Fatigue Testing

Along with the job of installing gages and taking resistance readings, we embarked on a fatigue testing program to try to find out what the endurance limit of the steel is, to try to model some of the



XBB 691-184

Fig. 20. S/N gages with auxiliary terminals.



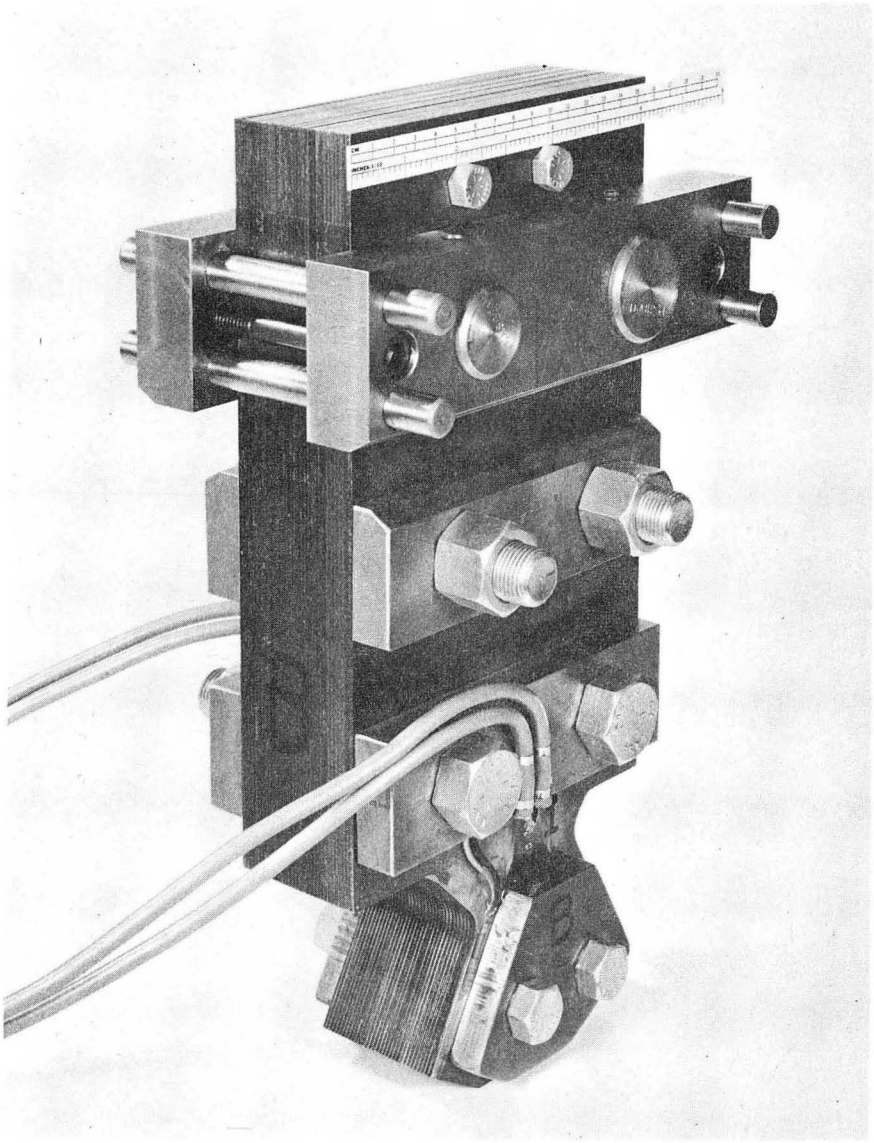
XBB 691-619

Fig. 21. Cover plates in place.

assembly forces in order to determine their magnitude, to see how these affect the endurance limit, and to find out as much as possible about the S/N gage characteristics.

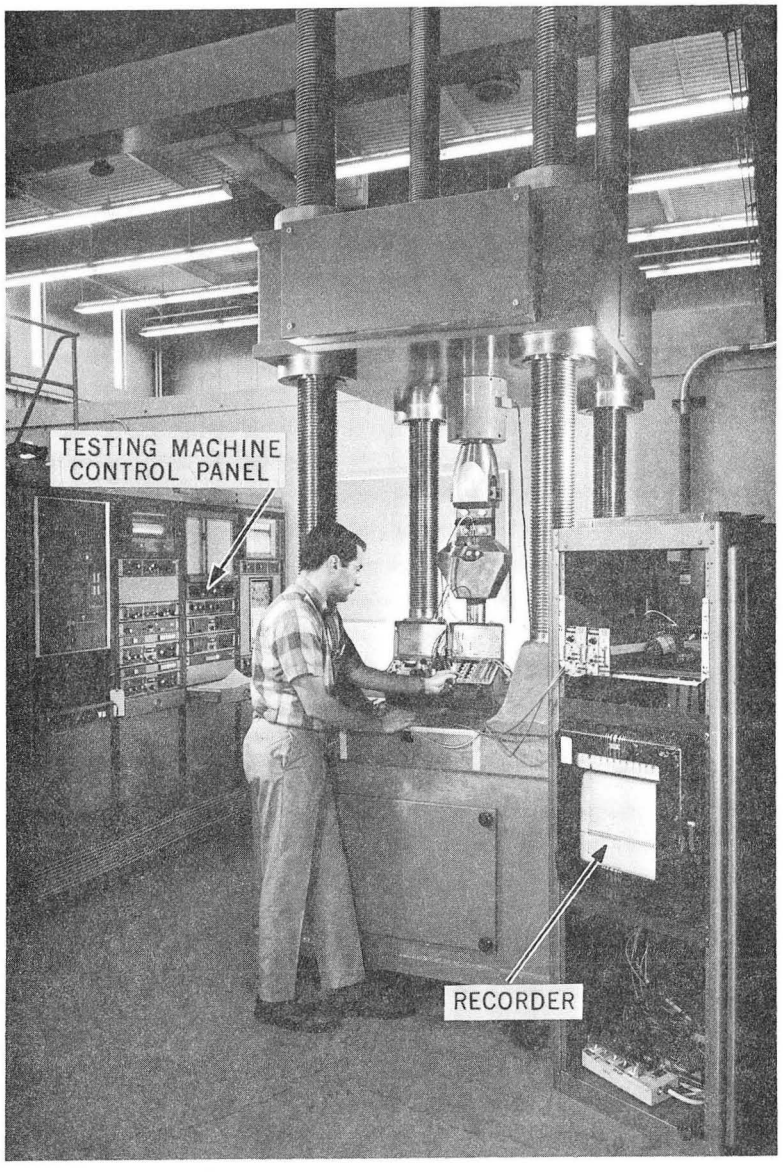
It is very difficult to get a good modeling of this dovetail connection because of the various unknown force magnitudes; however, it was decided to take some of the original laminations from poles that did not fail and make up 2-inch stacks of laminations (Fig. 22), anchor them in a method similar to that used in the generators, and cycle these packages. We used the laminations in the "as punched" condition for some samples, while others were ground in the dovetail area to remove the hard, brittle edge. We used a 300 000-lb universal testing machine (Fig. 23) for our studies. We bonded fatigue life gages (#1 and #2), one on each face of the sample, in the area next to the wedge to monitor fatigue life, and installed strain gages (#1 and #2), again, one on each face, at the neck of the dovetail to monitor the total tension load on the sample (see Fig. 24). This load, as determined by the strain gages, is somewhat fictitious, since we can gage only the two end laminations, which we have called faces #1 and #2. (This is also the case with the generators, however). Therefore, we do not know what the loads are on other laminations. We hope that the shim distributes the load adequately, but this may be wishful thinking. Recognizing these limitations, we thought we would attempt the testing anyway.

Even though the dovetail grip appears to be quite stiff we found that with the magnitude of the tension loads applied to the samples--up to 125 000 lb--the jaws opened slightly and therefore did not maintain



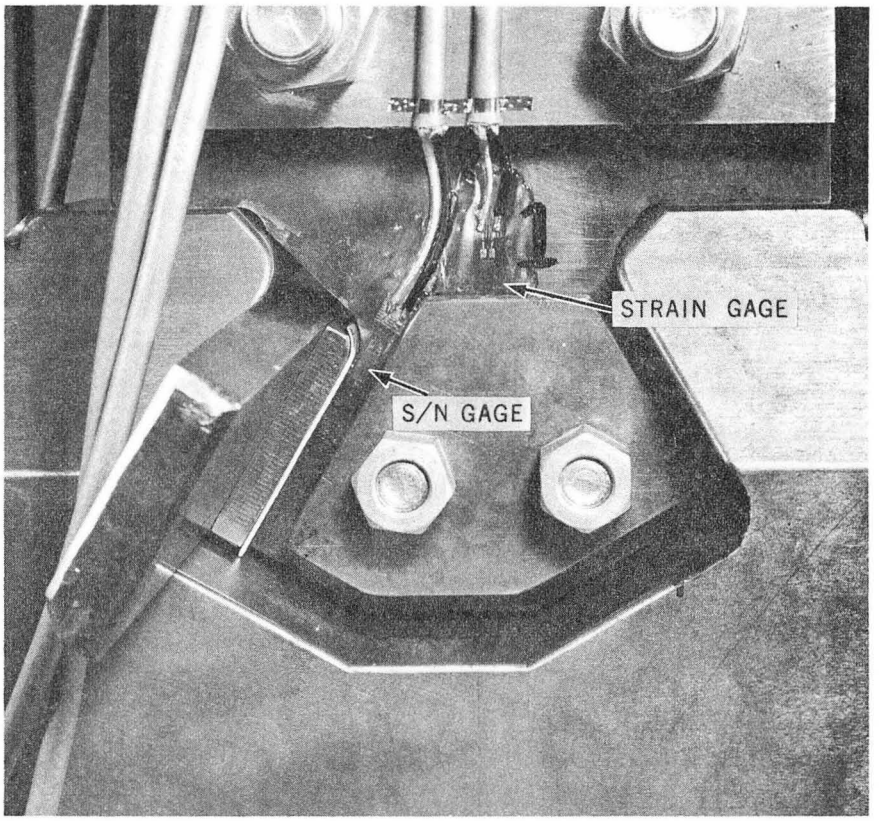
XBB 688-4787-A

Fig. 22. Laminated dovetail fatigue sample.



XBB 686-3309-A

Fig. 23. Sample installed on universal testing machine.



XBB 686-3311-A

Fig. 24. S/N gage and strain gage on dovetail sample.

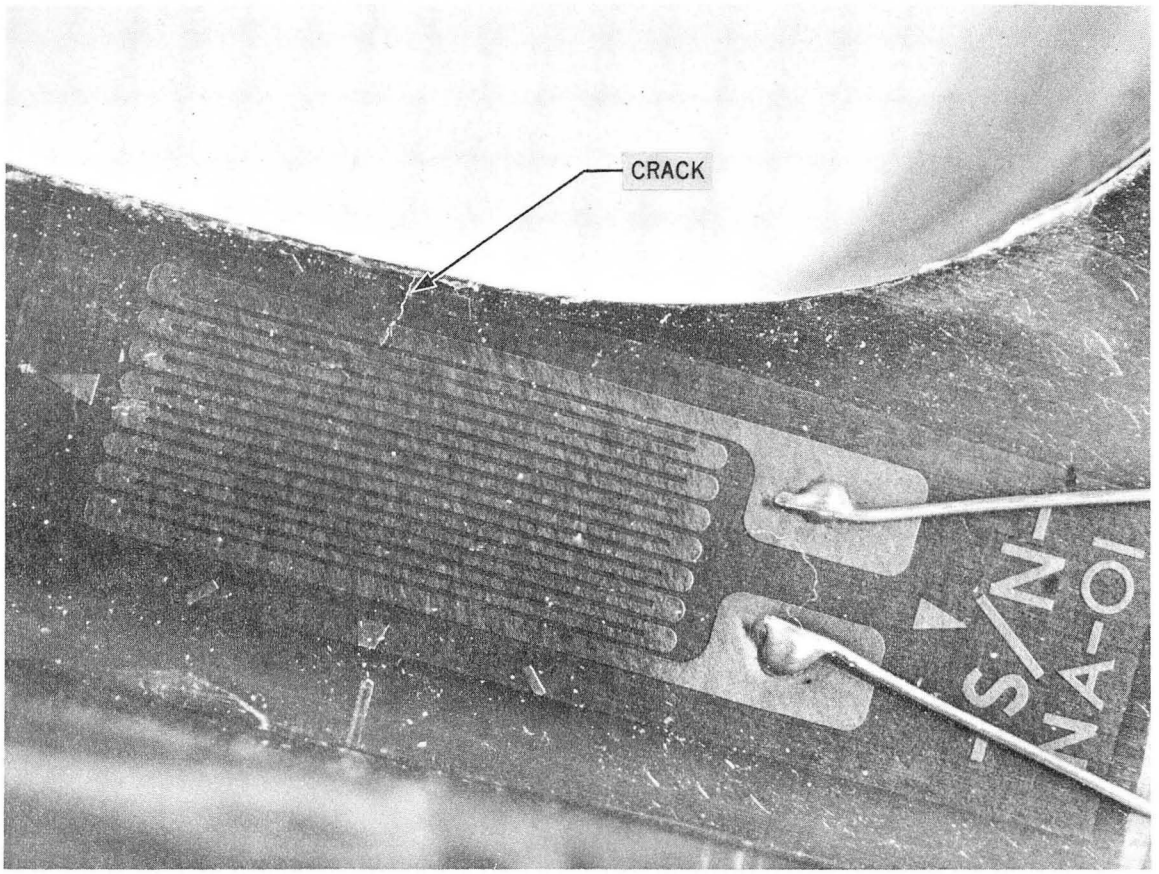
the necessary preload on the side of the dovetail. In testing the first sample, sample A, we simply drove the wedges as hard as we could and tried to get it to fail in a reasonable length of time.

After experimenting with several mean and cyclic loads, we settled on a mean axial load of 105 000 lb and a cyclic load of plus and minus 20 000 lb at a frequency of 10 Hz, the machine's maximum at these loads and the frequency used for all our testing. At the corner of the wedge this creates a theoretical stress in the laminations of 46 500 plus and minus 9 350 psi.

These stresses are difficult to calculate and interpret, and are presented only to give some idea of their magnitude in relation to the strength of the lamination steel.

At 293 086 cycles the resistance in S/N gage 1 started to increase, and 49 500 cycles later, the gage failed--a crack had ruptured the gage. See Fig. 25. We define failure as the appearance of the first crack, which fails the gage. We had continuous resistance monitoring with a two-channel recorder, one channel for each S/N gage. When the gage failed and open-circuited, the recorder shut off the machine. (The recorder is interlocked with the testing machine, so that when the gage open-circuits and causes full-scale recorder deflection, it automatically shuts the machine off.) The interesting thing is that, once the machine was shut off, the load relaxed and the gage grid ends made contact again, thus closing the circuit, as can be seen in Fig. 26, a reproduction of the recorder trace.

Upon photographic and microscopic examination we verified the existence of the crack through the first strand of the gage and also in



XBB 686-3719-A

Fig. 25. Crack in dovetail sample A.

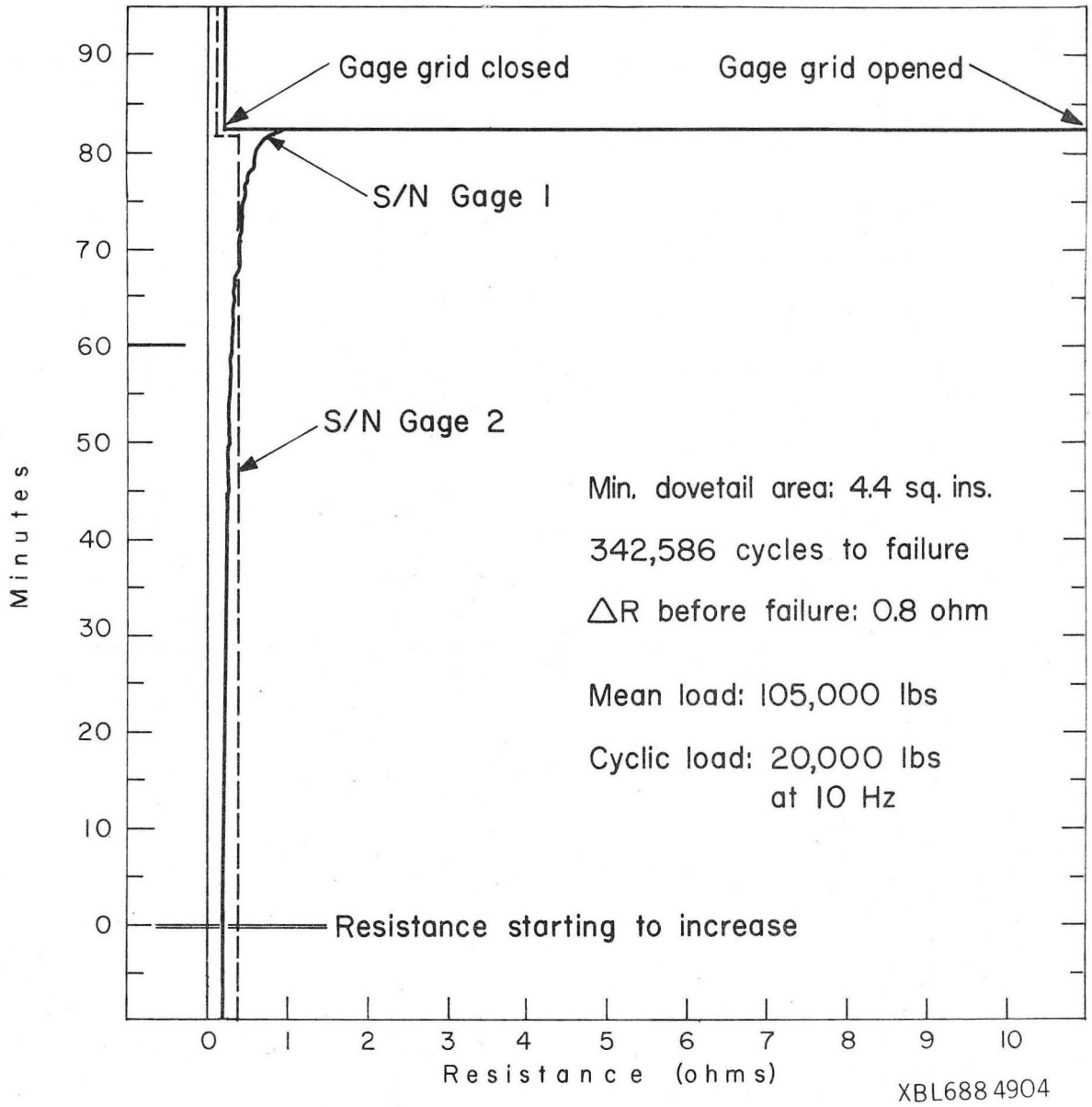


Fig. 26. Plot of S/N gage resistance vs time for dovetail fatigue sample A.

the steel. The ΔR (resistance change) just before failure was approximately 0.8 ohm. S/N gage 2 showed no resistance change. When it would have done so we do not know, for we stopped the test at first failure and removed the sample from the machine. See Table II for a summary of the results of our fatigue testing.

We do not know what the actual stresses were in the sample at the point where the wedge makes contact with the lamination, and, of course, at the location of the S/N gage. For this first trial we did not attempt to use the fatigue gage as a strain gage to determine the actual wedge loading.

In the second trial, to try and solve the "flexible" jaw problem, we shrunk-fitted the sample, sample B, into the jaw to try to preload the dovetail with the jaw as well as the wedges. We heated the jaw to 500°F, inserted the dovetail sample, and quickly drove the wedges with a hammer. This did not prove very effective, as the jaws still expanded when the sample was loaded.

The strain in the fatigue life gages, as determined with the S/N gages connected to a strain indicator, due to the wedge's pushing on the edge of the lamination, averaged about 1100 $\mu\epsilon$ (microstrain or microinches/inch) at the maximum axial load of 107 500 lb (mean plus cyclic). It is difficult to interpret this information, since the load from the wedge is normal to the edge of the lamination and the fatigue gage measures strain parallel to the lamination edge. The strains during the test, as indicated by the fatigue life gages and the strain gages, are presented in Table II. The difference between the plus and minus values was probably due to the complicated dovetail shape and anchor. The

Table II. Fatigue testing summary.

SG = strain gage; S/N = fatigue life gage;
ΔR = change in resistance; $\mu\epsilon$ = microstrain (μ in./in.).

Sample (laminations as punched)	A	B	C
Mean load (lb)	105,000	82,500	82,500
Cyclic load (lb)	±20,000	±25,000	±25,000
SG #1 mean strain ($\mu\epsilon$)	492	352	223
SG #1 cyclic strain ($\mu\epsilon$)	+92 -88	+125 -116	+107 - 89
SG #2 mean strain ($\mu\epsilon$)	-	236	260
SG #2 cyclic strain ($\mu\epsilon$)	-	+122 - 81	+117 -106
S/N #1 mean strain ($\mu\epsilon$)	-	895	575
S/N #1 cyclic strain ($\mu\epsilon$)	-	+497 -337	+383 -303
S/N #2 mean strain ($\mu\epsilon$)	-	588	636
S/N #2 cyclic strain ($\mu\epsilon$)	-	+515 -234	+425 -372
Cycles to ΔR - S/N #1	293,086		435,461
Cycles during ΔR - S/N #1	49,500		45,000
Cycles to failure - S/N #1	342,586		480,461
ΔR just before failure - S/N #1 (ohm)	0.8	a	0.4
Cycles to ΔR - S/N #2	-		471,461
Cycles during ΔR - S/N #2	-		153,000
Cycles to failure - S/N #2	-		624,461
ΔR just before failure - S/N #2 (ohm)	-		1.68

a. Failure not seen by S/N gages. Crack did not propagate under gages. Total cycles: 2.2 million.

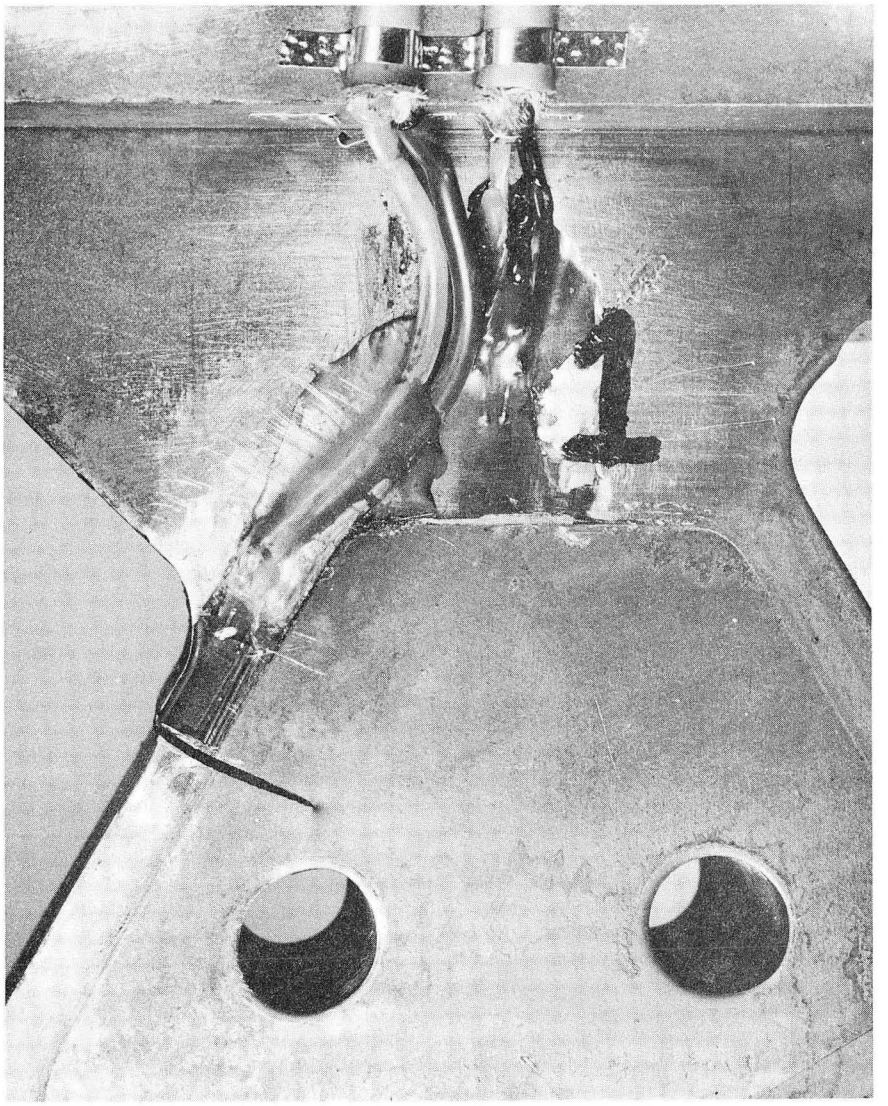
theoretical stress at the wedge corner was 36 300 ± 23 100 psi.

Unfortunately, when the wedges were driven during assembly, they slipped, and the corner of the wedge was below the fatigue life gage grid. We were apprehensive about this test, since, unless the crack propagates under the gage, the gage will not give an indication of failure. Previous experience has shown that the crack starts at the corner of the wedge.

We ran for 2.2 million cycles, with a mean axial load of 82 500 lb and a cyclic load of ± 25 000 lb, and saw no evidence, from the fatigue life gages, of failure. But failure did in fact occur as shown in Fig. 27--a crack developed, though not under the gage. Prognostication was fulfilled, unfortunately. We noticed the crack upon disassembly of the apparatus. This area was unobservable during the test because the gage coating was darkened by the heat from the hot jaw. As a result, we could not determine when the crack appeared. This coating and a cover plate were removed for this photograph.

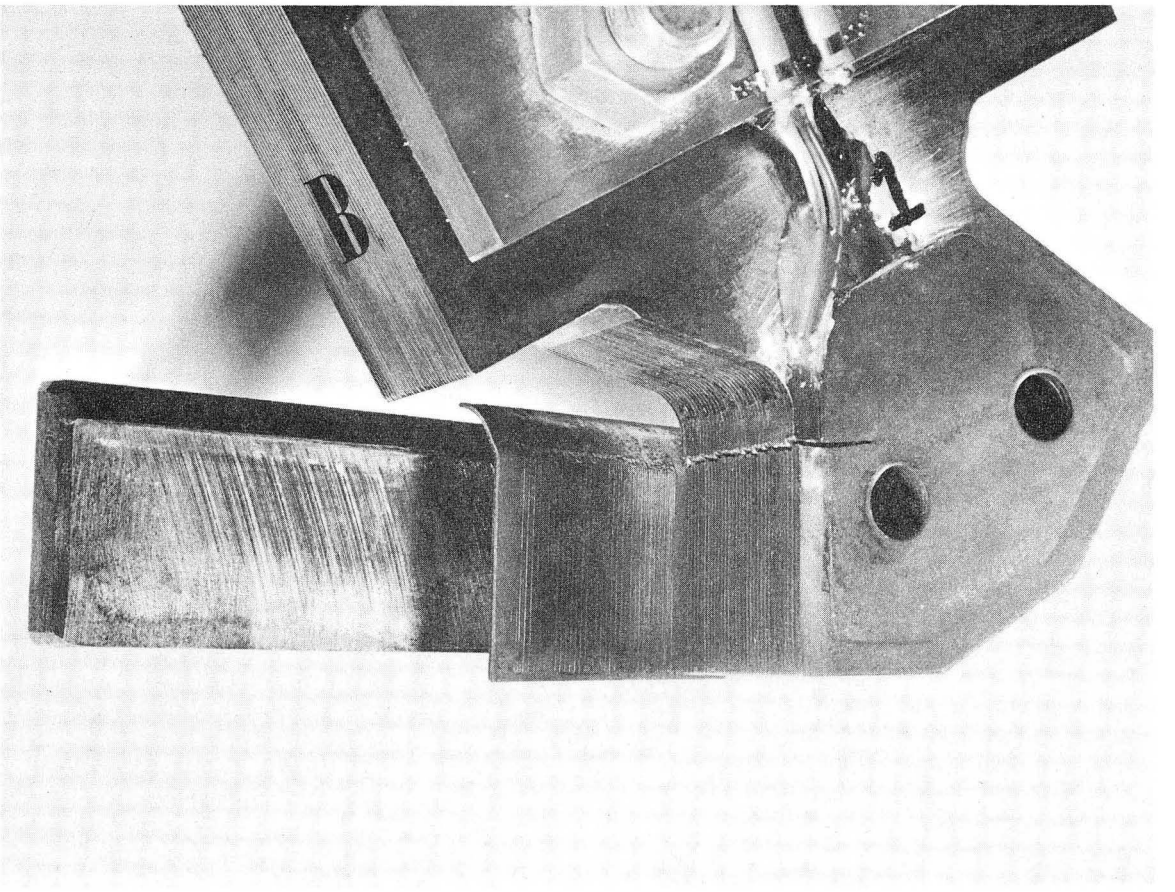
Note the severity of the failure in Fig. 27 and Fig. 28. Even though the bolt hole and the general area near the gage were distorted, the gage gave no indication that anything was happening. Obviously there had been considerable preload on this dovetail.

For sample C we fabricated a clamping fixture that incorporates two 30-ton hydraulic jacks to squeeze and hold the jaws together, thereby greatly increasing and maintaining the preload on the dovetails. This more closely duplicates the stiff condition of the actual generator rotor. See Fig. 29.



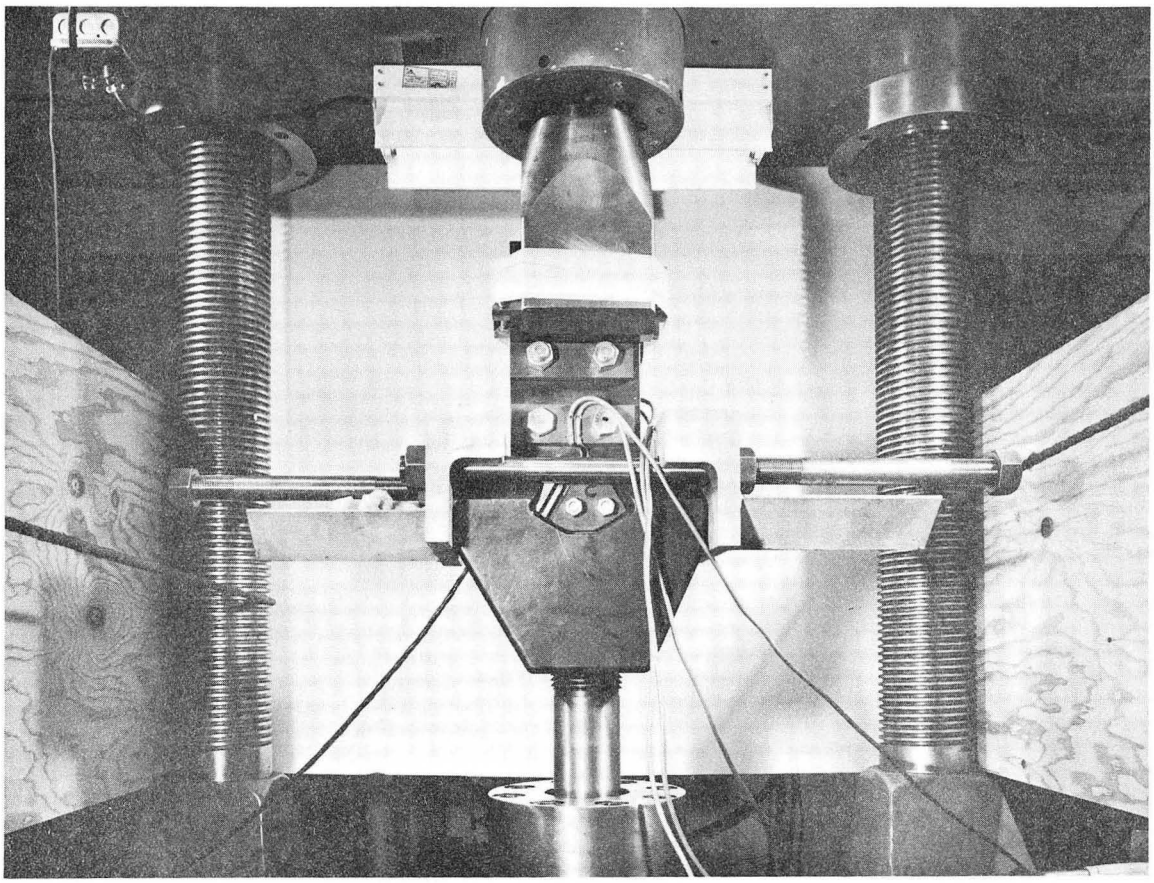
XBB 695-2949

Fig. 27. Sample B failure, side 1.



XBB 698-2948A

Fig. 28. Sample B with wedge and shim.



XBB 696-3868

Fig. 29. Sample C, jaw clamping fixture (30-ton jacks are removed).

We assembled this apparatus on the testing machine and applied 60 tons of force with the hydraulic jacks. This resulted in a fatigue gage strain reading of 1676 $\mu\epsilon$ on S/N gage 1 and 1347 $\mu\epsilon$ on S/N gage 2. Obviously, as was expected, the wedge is not bearing evenly on at least these two end laminations. This is probably similar to the condition on the generators. We then applied the total axial load of 107 500 lb with the machine (mean plus cyclic loads)--we decided on another try at 82 500 ± 25 000 lb. S/N gage 1 registered 7 480 $\mu\epsilon$ and S/N gage 2 read 11 900 $\mu\epsilon$. Both gages indicated that there was local yielding, as the strains would not stabilize under a static load. We removed this load and found a zero shift of 6693 $\mu\epsilon$ and 10 463 $\mu\epsilon$ on S/N gages 1 and 2 respectively.

We rebalanced the strain indicator and again applied the 107 500-lb load. The strains were still unstable, so we increased the load to 110 000 lb. We held this higher load for about 5 min and then reduced the load to 107 500 lb, and found that indeed things were now stable. The instability of the S/N gages, as we had expected, was due to the high load on the edge of the laminations because the corner of the wedge was digging in and causing a slow yielding condition. During all this, the two strain gages at the neck of the dovetail behaved perfectly--the strains were reproducible with no zero shift.

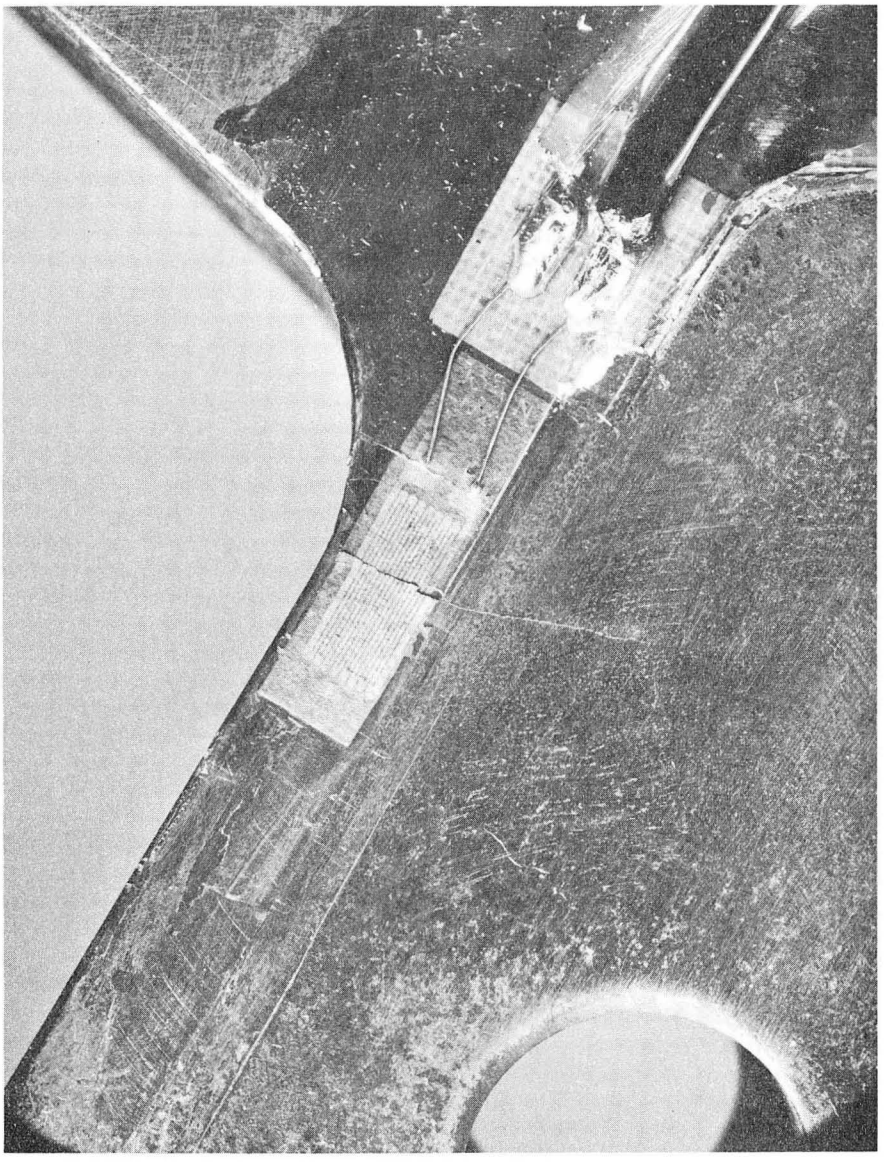
We slowly cycled the sample from zero to maximum load until the strains from the S/N gages were reproducible, indicating that the assembly had had the kinks worked out and that the loads would not shift. We suspected that since the wedge was severely digging into the laminations, we probably wouldn't have to wait too long for failure once we

started testing this sample.

We started the test with a load of 82 500 ± 25 000 lb. This produced a strain parallel to the lamination edge, as determined by using the fatigue gages as strain gages, of about 600 $\mu\epsilon$ plus 400 $\mu\epsilon$ and minus 340 $\mu\epsilon$. See Table II for the actual values. The theoretical stress at the wedge corner was 36 300 ± 23 100 psi.

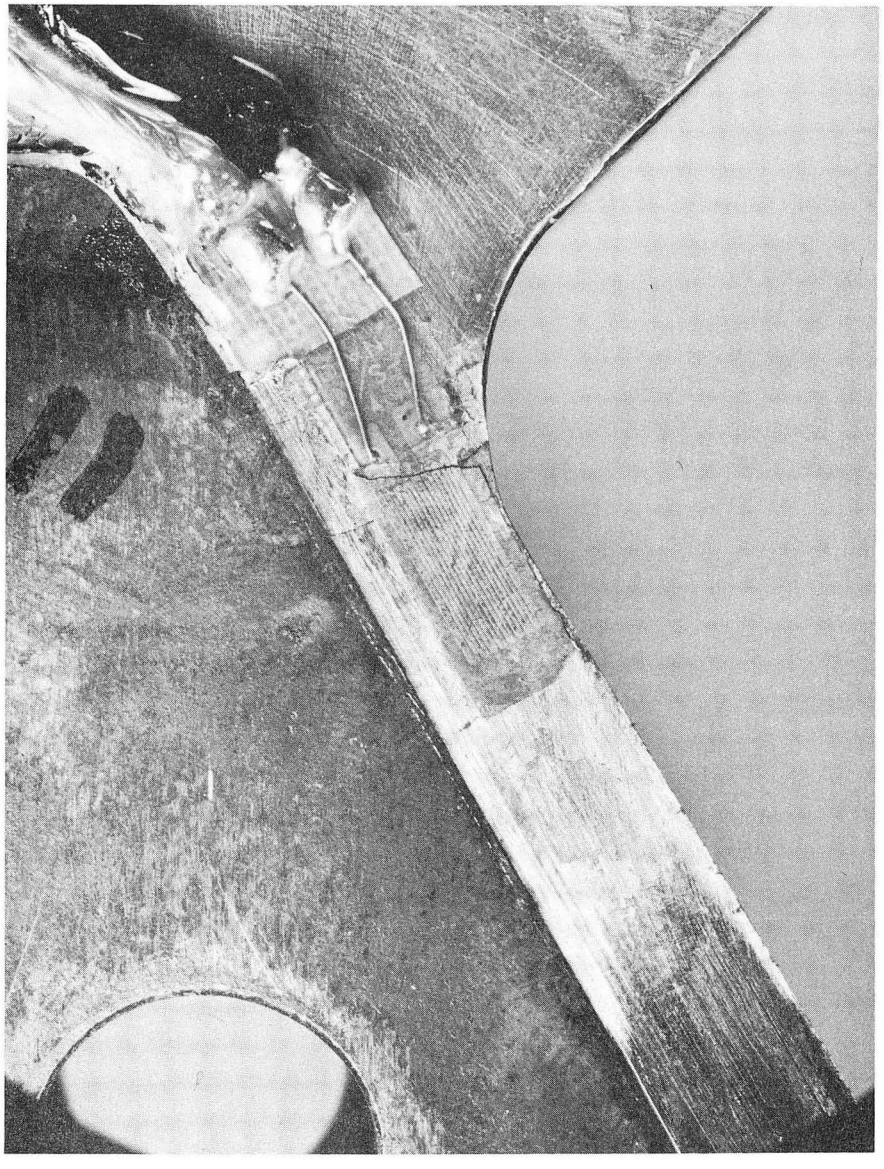
At 435 461 cycles the resistance of S/N gage 1 started to change; 45 000 cycles later S/N gage 1 failed. The ΔR just before the failure was 0.4 ohm.

S/N gage 2, at 471 461 cycles, started to change resistance. Approximately 153 000 cycles later it failed, with a ΔR just before failure of 1.68 ohms. This was 144 000 cycles after gage 1 failed. We let the machine run for 46 500 more cycles to see how the crack would develop, and then removed sample C from the machine. The shapes of the recorder traces of the changes in gage resistance in samples A and C were similar (Fig. 26). There was a gradual resistance change as the crack developed and headed for the gage. Then as the crack propagated under the gage, the resistance change was quite rapid up to failure. Figure 30 shows S/N gage 1 and Fig. 31 shows S/N gage 2. Figure 32 shows the side of the dovetail, and it is quite evident that all laminations have failed, and that they have failed at the point where the corner of the wedge was making contact. By now we have certainly proved that the stress concentration due to the corner of the wedge causes the failure. Note the rough "as punched" lamination edges in Fig. 32. Is it any wonder that they are full of microcracks to start with?



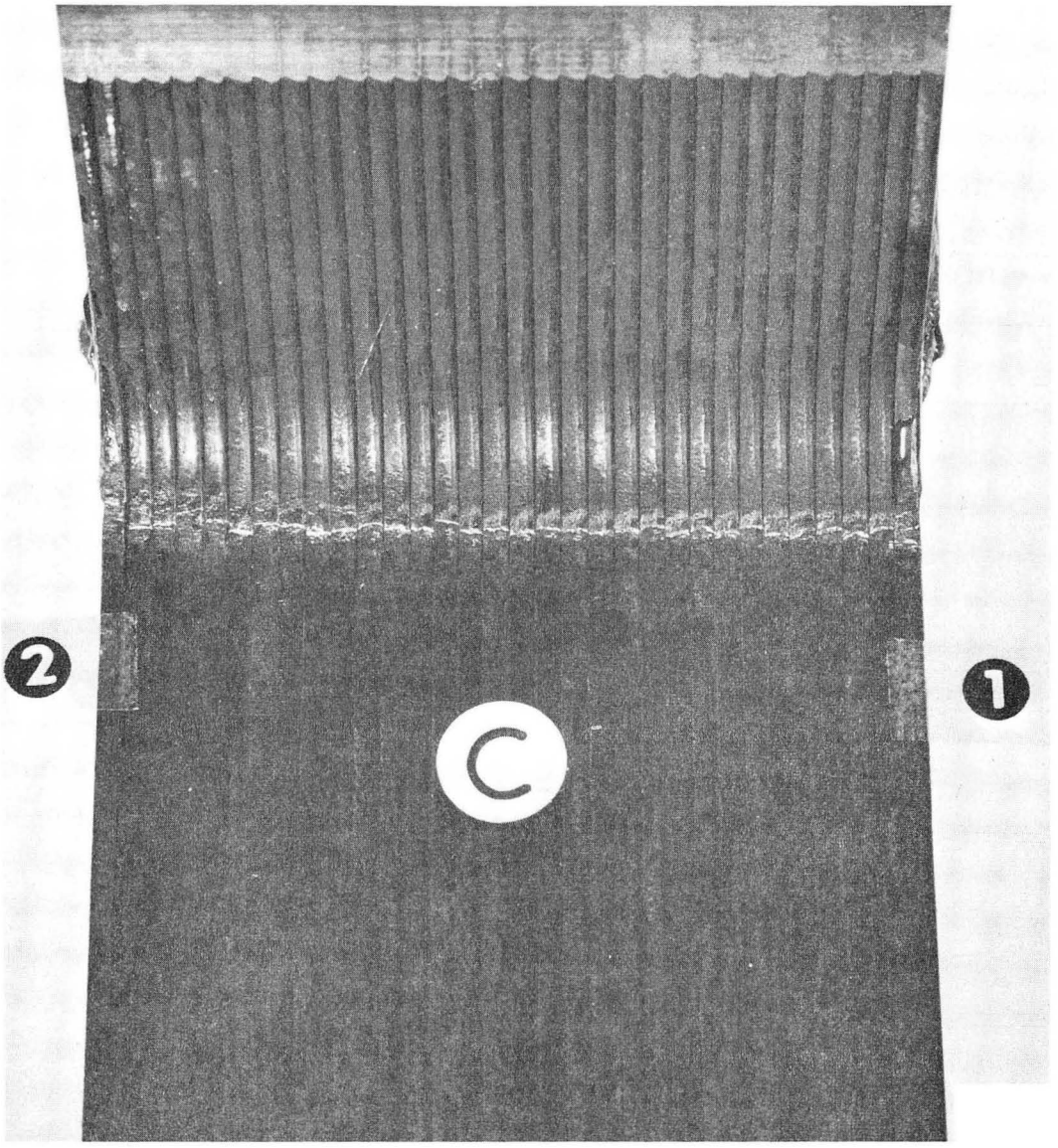
XBB 696-4060

Fig. 30. Sample C, S/N gage 1.



XBB 696-4059

Fig. 31. Sample C, S/N gage 2.



XBB 696-4058

Fig. 32. Sample C, wedge side of dovetail.

To date all the fatigue testing has been performed with samples made from "as punched" laminations. In the fall of 1969 we will test the ground samples to try to determine how much effect the removal of the punched edge has on the fatigue life of the lamination steel.

SUMMARY AND CONCLUSIONS

In looking back we feel extremely lucky; we feel that possibly early in the game very small cracks were developing in the original poles, but since the dovetails were covered, we were not aware that we had a problem until there was actual physical movement of the pole. We shudder to think what might have happened if the poles had started scraping the stator windings under full excitation.

One sure way to reduce the fatigue problem would be to reduce the speed change during a pulse which reduces the cyclic stresses, and this has been done. By redesigning some of the electronics it was possible to cut the speed change in half, from 100 rpm (875 to 775 rpm) to 50 rpm (875 to 825 rpm). We now expect the poles to last for 4 yr—perhaps for the life of the Bevatron.

It's mystifying to us just why all the new cracks appeared in poles 6 and 7. East and West machines both developed cracks in gage positions 7-2 in the south end. Pole 6 in the West generator at the north end was the one in which the original failure was first noticed, and in the original failures it was the only pole that suffered cracks completely across both dovetails. Subsequentely we had a new crack in WN 6-4 that was difficult to stop. It might be just a coincidence, or it might have real significance. So far, all the new cracks have been on the wedge side of the dovetail.

We recognized from the beginning that we probably would not be able to use fatigue life gages as predictors of life on these machines for two reasons: they are not a good metallurgical match to the steel, and secondly, most of the gages were not put on at startup. In other words, we put on four gages each week over a period of one and a half years; some of them have seen more fatigue history than others, and this makes prediction information very difficult to correlate.

Although we recognized these limitations of the gage in our particular application, it has been extremely valuable to us. The cracks, unless they were quite large, could not have been seen without a magnifying glass plus a knowledge of exactly where to look. Reading S/N gages is certainly much neater and faster than using dye penetrants or magnetic-particle inspection techniques. Darrell Harting's[2] instructions to me were certainly correct: the gage will tell you that things are happening, and it's just a matter of sorting out the information and becoming familiar with what the gages tell you. In general I can say that the S/N gage is an extremely valuable tool.

ACKNOWLEDGMENTS

I wish to thank several people for their assistance on this fatigue life gage program: Darrell Harting of the Boeing Company and James Starr of Micro-Measurements for their invaluable information and helpful suggestions; Doug McWilliams of the Lawrence Radiation Laboratory Photography Department for his outstanding effort in developing the photographic techniques needed; Hans Krapf, my lead technician, for his tireless efforts in developing the installation techniques required in this miserable environment; and Rosemary

Barrett for her many hours of editing and general assistance in the preparation of his manuscript.

REFERENCES

1. Application Manual, Micro-Measurements, Inc., Romulus, Michigan, August 1966, Appendix I.
2. D. R. Harting, The S/N Fatigue Life Gage: A Direct Means of Measuring Cumulative Fatigue Damage, Exptl. Mechanics, 6 [2], 19A (1966).

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

TECHNICAL INFORMATION DIVISION
LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720