UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

BEFORE THE ATOMIC SAFETY AND LICENSING APPEAL BOARD

In the Matter of VIRGINIA ELECTRIC AND POWER COMPANY (North Anna Nuclear Power Plant, Units 1 and 2)	Docket Nos. 50-338 O.L. 50-339 O.L.

NRC STAFF TESTIMONY OF WARREN S. HAZELTON
AND CLIFFORD D. SELLERS REGARDING
TURBINE DISC CRACKING

Q. Mr. Hazelton, please state your name and position with the NRC.

A. My name is Warren S. Hazelton. I am Section Leader of the Materials Application Section in the Materials Engineering Branch of the Division of Engineering within the Office of Nuclear Reactor Regulation of the Nuclear Regulatory Commission.

Q. Have you prepared a copy of your professional qualifications?

A. Yes. A copy of my professional qualifications is attached to this testimony.

Q. Mr. Sellers, please state your name and position with the NRC.

A. My name is Clifford David Sellers. I am a Principal Materials Engineer in the Materials Engineering Branch of the Division of Engineering within the Office of Nuclear Reactor Regulation of the Nuclear Regulatory Commission.

Q. Have you prepared a copy of your professional qualifications?

A. Yes. A copy of my professional qualifications is attached to this testimony.

Q. Gentlemen, what is the purpose of this testimony?

A. This testimony addresses certain questions raised by the Appeal Board in the North Anna 1&2 Operating License proceeding regarding the matter of turbine disc cracking and its connection to the issue of the risk of turbine missiles at the facility.

Q. What is your understanding of the concerns of the Appeal Board on this issue?

A. During the course of the Appeal Board's review of the Licensing Board's decision in this operating license proceeding, the Appeal Board raised two safety issues on its own initiative. On June 18-20, 1979, an evidentiary hearing was conducted on both issues. One of the issues, the continuing settlement of the ground beneath the service water pumphouse, was disposed of by the Appeal Board in its decision dated February 11, 1980 (ALAB-578).

In that decision, the Appeal Board reserved decision on the other plant safety issue, that relating to turbine missiles (i.e., the likelihood that pieces of the turbine would break off and cause unacceptable damage -- in terms of safety consequences -- to other plant systems). That decision was held up because new developments bearing on the resolution of the turbine missile question had been brought to the attention of the Appeal Board. Specifically, cracking of turbine discs had been uncovered at a number of facilities employing equipment made by the same manufacturer that supplied the North Anna turbines.

Upon reviewing submittals from the Staff and Applicant on the disc cracking problem, the Board concluded that the submissions justified continued operation of North Anna 1, that an inspection of its turbine should take place, and that the parties should provide further information regarding the long-term significance of the disc cracking phenomenon. Specifically, the Appeal Board requested the parties to address what has been ascertained regarding the causes of the early cracking, as well as the steps being taken to correct the problem. This testimony addresses these concerns.

Q. What prompted the investigation into the Westinghouse turbine disc cracking problem and the related actions taken by the Staff?

A. The NRC was informed in November, 1979 that stress corrosion cracks were found in some Westinghouse turbine discs during refurbishing operations, and that Westinghouse was recommending that turbines with significant service experience should be inspected for cracking at the earliest convenient opportunity. At that time, the turbine at Zion Station Unit No. 1 was being inspected, and some cracks were found and reported to the NRC.

On Dec. 17, 1979, Westinghouse made a presentation to the Staff regarding the cracking, and provided additional information on the Westinghouse recommendations and inspection schedules. At the Staff's request, Westinghouse formed an owners group to address the turbine disc cracking incidents. Westinghouse established a support team with a full time cognizant manager to provide a communication link between the company and the owners group and to provide timely responses to Staff requests.

Q. What was the basis for these inspection schedules?

A. Westinghouse used their judgement to determine which turbines had discs that were likely to crack, estimated how fast these cracks would grow, and proposed to inspect before such postulated cracks would grow to the critical size to cause failure.

Q. Did the Staff review this basis and find it acceptable?

A. The Staff did perform their own evaluation of the postulated crack growth rates and critical crack sizes, using information provided by Westinghouse as well as other technical information available. Frequent meetings were held with Westinghouse and the owner's group to apply the data being developed from the ongoing inspections. This activity provided a progressively improved basis to quantify crack growth rate estimates. Although criteria used by the Staff were generally somewhat more conservative than those used by Westinghouse, we were in general agreement.

Q. Did this inspection program prevent disc failures?

A. Yes, with one exception. According to calculations, the Yankee Rowe discs could have cracks large enough to cause failure, and therefore an immediate inspection was deemed by the Staff to be very desirable. Unfortunately, specific design details of this early model turbine precluded inspection of the suspect area without an extensive outage, so the utility decided to postpone the inspection until the next refueling outage. The turbine failed during start-up. Examination of the failed disc showed many stress corrosion cracks of a size consistant with our crack growth and critical crack size calculations.

Q. What is the current status of the turbine inspection program?

A. As more turbines were inspected, and more data on crack sizes was obtained, both Westinghouse and the Staff continued to refine their criteria. Further, after all turbines with significant service life had been inspected, enough data had been accumulated to permit Westinghouse to derive crack growth rate predictions using statistical methods. They have prepared a proprietary report, "Criteria for Low Pressure Nuclear Turbine Disc Inspection," MSTG-1-P (VEPCO's proposed Exhibit V-1), covering their current crack growth rate and critical crack size calculational models. The Staff has reviewed this report and has found it to be an acceptable basis for setting inspection schedules. We have informed all affected utilities that inspection schedules in accordance with the Westinghouse criteria are acceptable to the Staff.

Q. What conservatisms are applied in setting inspection schedules?

A. Using the best estimates of the maximum expected rate of cracking of each turbine disc, and calculated critical crack depths, the basic requirement is that turbines be inspected before any crack would grow to one half of the critical size. In cases where inspection has revealed small cracks, additional conservatism is applied by permitting further operation for only one half of the time calculated for the crack to grow to one half of its critical size.

Q. It appears that the effectiveness of this approach depends highly on the effectiveness and reliability of the inspection procedure. Have you made any evaluation of this?

A. Yes we have. We realize from the beginning that this would be vital to any effective program. To augment our expertize in this area, we engaged several expert consultants from the Sandia and Oak Ridge National Laboratories to review the inspection procedures in detail. Further, these consultants accompanied us to observe actual inspection being performed to better understand technical details and evaluate the reliability of the inspections. We are particularly interested in having a high probability of detecting a crack that is large enough to be a threat to disc integrity, or with continued operation, could grow to such a size before the next inspection. A crack about one inch deep would be in this category for most operating turbines, so we specifically asked our consultants to estimate the probability of detecting a one inch deep crack. They concluded that the reliability of detection of a one inch deep crack is very nearly 100%, which is in line with our own estimates. Reasons for believing in such a high reliability include:

1. The inspection method used is ultrasonic examination, which, when especially tailored for specific conditions and geometry can be nearly fool-proof.
2. The procedure and equipment used was specifically developed by Westinghouse for this purpose, and has been extensively checked out in their laboratory.
3. Flaw orientation problems, often the cause for not finding defects by ultrasonic means, are minimized because the disc cracks are usually multiple and highly branched. This means there is alway a reflective surface with favorable orientation present.
4. The specific Westinghouse procedure, unlike others commonly used, makes use of very high amplitude during search modes. "Noise" from the searched surface is always present, but indications from cracks have highly distinctive and instantly noticeable characteristics. The necessity for operator judgements or a constant high level of operator concentration is minimized.

Q. What are typical critical crack depths for Westinghouse turbines?

A. The actual value of calculated critical crack depths for operating turbine discs is considered by Westinghouse to be proprietary information. However, we can note that the deepest crack found in the failed disc in Yankee Rowe was around 1½ inches. On the other hand, several cracks about 3 inches deep were found in a number one disc in the Cooper Station turbine. These cracks did not cause failure of the disc and, therefore were not yet of critical depth for normal operating speed.

Q. How do you estimate the size of crack necessary to cause disc failure?

A. The crack size (A crit) that could cause disc failure depends on several parameters. The calculations relating these parameters use the well proven concepts and methods of linear elastic fracture mechanics (LEFM). It is important to note that a critical crack for failure could be a long, shallow one, or a short, deep one. The shape of the crack is, therefore, very important. Accordingly we first note the shape of the real cracks and then perform our calculations to determine what the critical depth would be, for a crack with such shape. This is discussed in more detail later, but it should be noted that cracks are found in two typical locations, in the keyways cut into the disc bore, or in the bore away from the keyways. A schematic drawing of a typical turbine disc showing these locations is provided in Fig. 1.

The fracture mechanics formulation used is a standard one used for disc burst analysis and is well known and accepted. It was been verified by actual burst tests run in various laboratories, including those of Westinghouse and General Electric. For the specific configurations of interest here, it is considered to be slightly in error on the conservative side, that is, it results in predicted critical crack depths somewhat smaller than are actually required to cause failure.

The important material parameter for determining A crit is the Critical Stress Instensity factor (K_{IC}), which is obtained by direct measurement using standard specimens and test methods, or by standard correlation methods developed to convert results from the simpler Charpy V impact test to K_{IC} values. The specific LEFM formulation for critical crack depth (A_{crit}) calculation for cracks in disc bores is:

$$A_{crit} = \frac{Q}{1.21\pi}\left(\frac{K_{IC}}{\sigma}\right)^2$$

Where:

σ: Is the nominal stress at the bore

Q: Is a complex function related the shape of the assumed crack

If the crack is in a keyway, the depth of the keyway is considered part of the crack. Q varies with the shape of the crack and the ratio of the applied stress to the yield strength of the material.

In the case of turbine discs, Q varies from 1.0 for a crack 20 times as long as it is deep to 2.3 for a crack twice as long as it is deep. Because Q affects the critical crack depth in a linear manner, it is important to know the probable shape if the calculation is to be meaningful. Westinghouse originally calculated critical crack sizes using a postulated shape of 10 to 1. This now appears to be overly conservative, as it results in calculating critical crack depths less by a factor of 2.3 (the ratio of the Qs) than if a shape of 2 to 1 is assumed, for example. Now that many cracks been found, more realistic shapes can be used. Based on evaluation of all cracks found to date, we now consider that the critical depth of keyway cracks should be calculated assuming they are four times as long as they are deep, but cracks in the bore away from keyways should be considered to be only twice as long as they are deep. The determination of K_{IC} value for each disc is done in a very simple manner. Actual K_{IC} measurements are not practical, so standard correlations with the results of the Charpy V impact tests performed on each disc are used as a basis. The correlation we and Westinghouse use was developed some years ago by Rolfe and Novak of the U.S. Steel Research Laboratory. It is an empirical expression that has been shown to be sufficiently accurate for steels of the type used for turbine discs. Parameters of interest are the yield strength of the steel and the absorbed fracture energy measured by standard Charpy V impact tests:

$$K_{IC} = \text{Yield Strength} \times \sqrt{5\left(\frac{\text{Charpy V Energy}}{\text{Yield strength}} - 0.05\right)}$$

As each disc has different strength and Charpy properties, the calculation is performed for every specific disc of interest.

Q. Have stress corrosion cracks been found in turbines made by other companies than Westinghouse?

A. Yes. As a result of the concern developed by the Westinghouse cracks, General Electric has been performing turbine inspections during the past several years. Up until recently, no clear evidence of cracking was found, although some questionable indications described as "water-cutting" were reported. Recently, large indications were found in a wheel (GE calls them "wheels" instead of "discs") at the Monticello plant. The wheel was removed, and the indications were verified to be stress corrosion cracks. General Electric now believes that many of the indications found earlier in other turbine inspections were also from stress corrosion cracks. They have initiated a stepped up inspection schedule for turbines with long service life. We are now evaluating this new information, but at present, we believe that it only confirms the validity of our current understanding of the problem.

Q. What is the cause of the cracking, and how is the postulated rate of cracking determined?

A. The mechanism causing the cracks is usually referred to as stress corrosion cracking. Simply described, this refers to a phenomenon that occurs when a specific material, often in a specific metallurgical state, is subject to cracking when stressed while being exposed to a specific environment. Studies of stress corrosion cracking phenomena aim to quantify these various factors. A typical study would be to determine for a specific material, how much stress it could withstand without cracking when exposed to a specific environment. Others might be aimed at finding out how fast a crack will grow under a specific set of conditions.

In general, we are talking only about aqueous environments, or at least environments where moisture is present. High strength steel alloys are subject to stress corrosion cracking in many wet environments; and the interactions between strength levels, composition, heat treatment, stress levels and literally hundreds of environmental conditions have been and still are being studied intensively.

In 1969, the turbine for the British Hinkley Point Plant failed. The British determined that the cause was the growth of stress corrosion cracks to critical size. In the major investigations that followed, they discovered that many turbines had cracked discs, and over the next decade performed many laboratory test to try to pinpoint the problem, and to sort out the importance of the many parameters.

All turbine manufacturers were vitally interested, and launched their own studies. Most of the results of the British work has been published, and much of the work of others has also been made public. Nevertheless, a great amount of information has been kept proprietary and Company Confidential. The situation can be summarized by saying that in most important areas, there is general agreement, but there remain some areas of disagreement. Because these areas of disagreement are relatively unimportant, they cause no problems to us in our regulatory role.

The major parameters, and where there is little disagreement, are these:

1. For cracking to occur, there must be moisture present. Dry discs don't crack.
2. The higher the temperature, within some limits, the greater will be the tendency to crack, and the faster the crack growth rate will be.
3. The higher the strength level of the steel, (and also therefore, the higher the stress level) the greater will be the tendency to crack, and the faster the crack growth rate will be.
4. Certain impurities, like caustics, some acids, and sulfides, will increase the tendency to crack, and/or cause cracking sooner.
5. After cracking has started, it proceeds at a generally constant rate until the crack becomes deep. At this

point it may slow down its rate of progression, or increase it's rate of growth, possibly depending on the stress level or enviromental conditions. For the types and depths of the turbine cracks we are concerned about, constant growth rate models best fit the service data.

6. Not all hot, wet discs crack. If they do crack, they apparently don't grow at equal rates, even at identical strength and stress levels, and at identical temperatures. It is not known whether this is due to minor differences in metallurgical state, stress state, or minor differences in the local environment.

One of the most striking examples of this was shown by the Yankee Rowe failure. The two number one discs were of identical design, were manufactured according to the same procedures, were made form the same steel ingot, and of course were subject to as similar temperature and environmental conditions as we could possibly hope to have. Yet one suffered hundreds of significant stress corrosion cracks, and the other had none.

Although it would be of enormous help of we could learn the reason or reasons for such differences in behavior, we make the assumption that every disc will crack as fast as the worst ones. Therefore we almost always "over predict" the size of any actual cracks, and are not surprized when an inspection shows that discs postulated to crack are found to be completely free of cracks. To make sure that turbines would be inspected before cracks grew to critical size, some crack growth rate model was needed. The Staff took the same type of approach that Westinghouse and the British did. We divided the depth of each crack found by the length of service on the disc to obtain an average rate of growth with time. We plotted this crack growth rate for each crack found on graph paper, as a function of the temperature at the crack location (furnished by Westinghouse). The "scatter band" covered most of the chart. Neverthless, an "upper bound" could be drawn, so at any given temperature there would be a rate above which no cases were found. When the crack growth rate data were separated according to the strength level of the specific disc, the "upper bounds" sorted out fairly well. While we were doing this evaluation, Westinghouse was taking the same general approach, and we often compared graphs and discussed various ways to improve them. As more and more crack growth rate data came from field inspections, most cases were enveloped by our upper bound curves. A very few times cracks were found that exceeded our "upper bounds", resulting in appropriate modifications. On the whole, however, the great majority of cracks were smaller than the maximum depth postulated.

Q. Will you describe the Staff's activities in this regard for the North Anna 1 turbine?

A. We performed calculations for critical crack depth, using information from Westinghouse supplied by the utility, for all operating turbine discs. We then used our maximum expected crack growth rate curves to determine when a "worst case" crack would grow to ½ of critical depth. We compared this with the utility's proposed inspection schedule to evaluate its adequacy. As our crack growth rate models changed, we updated our calculations.

We also performed these calculations for the North Anna 1 installation. We found that the planned inspection date, December, 1980, after approximately 24 months of operation was acceptable.

The worst postulated case, where the postulated crack would be closest to critical depth, was still less than ½ of the critical depth. Vepco requested a delay in the inspection until January 1, 1981 and the staff agreed to this extension, as the margin of safety was considered acceptable. Early in December of 1980 the NRC Staff learned of new information derived form the Farley Unit 1 turbine inspection, where cracks deeper than originally postulated were found. The Staff used that preliminary information in order to asses the effect the data might have on the Staff's crack growth rate model. By December 19, 1980, the Staff determined that the worst value for the ratio of the postulated crack depth to critical crack depth could be close to one for North Anna Unit 1 rather than the ½ that it previously calculated.

Because of this high value, and the potential impact it could have on the basis for continued safe operation of North Anna Unit 1, the Staff reexamined its evaluation of the potential for crack propagation in the turbine at North Anna Unit 1. The Staff also requested Vepco to provide it's written justification supporting continued operation until January 1, 1981.

The Staff determined that, based on overall conservatisms for the calculation of the critical crack ratio, continued operation until December 19, 1980, while the licensee gathered additional information was justified. On that date, the licensee met with the Staff to present its additional justification for continued operation. The Staff agreed to permit operation until January 1, 1981, when the inspection was performed.

Q. How did the postulated crack sizes agree with those actually found in North Anna No. 1:

A. The deepest crack found was 0.360" deep. This was slightly more than half of the maximum size originally postulated by the Staff before the data from Farley were available.

Q. What was the Staff's conclusion regarding further operation of the North Anna turbine?

A. The Vepco report on the Turbine inspection included an evaluation of further operation. It concluded that the rotor containing cracked discs could only operate for another six months before another inspection would be required. This was fairly consistent with our criteria. Vepco therefore decided to replace the entire rotor containing cracked discs with one then installed at Three

Mile Island No. 2. This rotor was inspected, found free of cracks, and installed at North Anna.

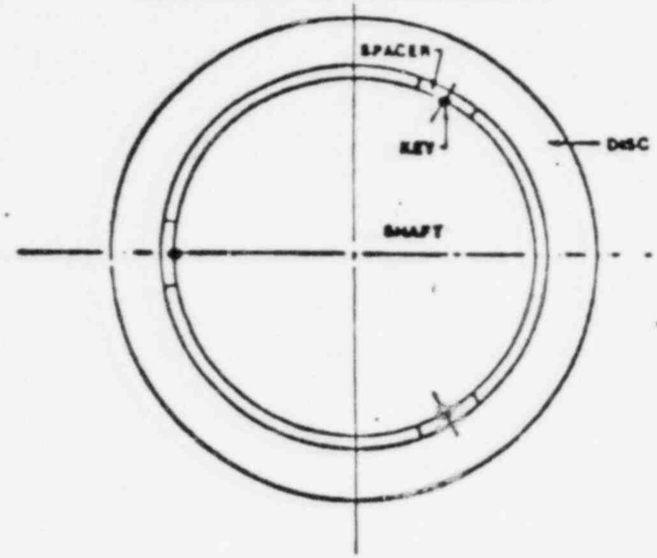
Q. What are the Staff's criteria for reinspection of the North Anna No. 1 turbine?

A. Our basic criteria remain unchanged. These are: a new disc, or a disc found free of cracks by inspection, can operate until the time calculated for a new crack to grow to one half of critical depth.

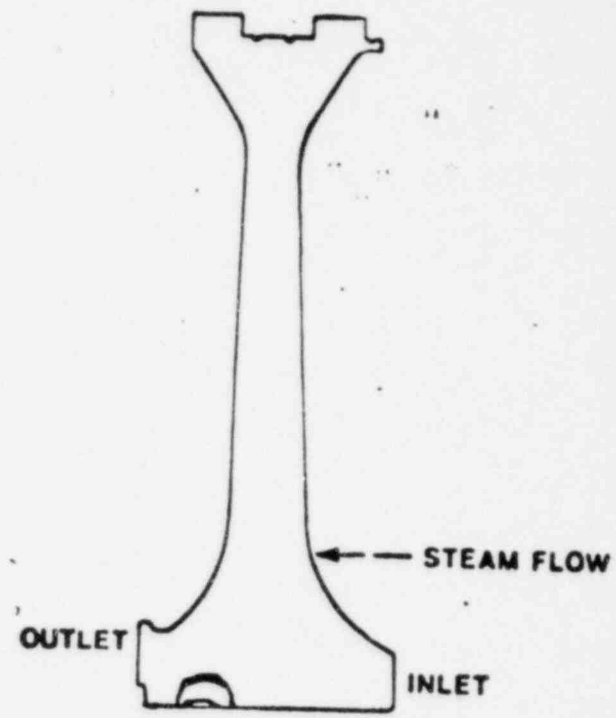
Q. What crack growth rate should be used for this calculation?

A. The utility should follow Westinghouse's recommendation, as indicated in our answer to an earlier question. To repeat, Westinghouse prepared a report describing the results of a statistical analysis of crack growth rates, crack shapes, and critical crack depth calculational models (see VEPCO's proposed Exhibit V-1). We have reviewed this report, and conclude that the inspection schedules derived by its use are consistent with our past criteria and current understanding of the cracking problem. These schedules provide the same margins in postulated crack size to critical crack size as we have been using and take no credit for containment of discs in case of failure. Adherence to these inspection schedules will provide an acceptably high degree of assurance that discs will be inspected before cracks can grow to a size that could cause disc failure.

END VIEW OF DISC SHAFT



BORE CRACK LOCATION



KEYWAY CRACK LOCATIONS

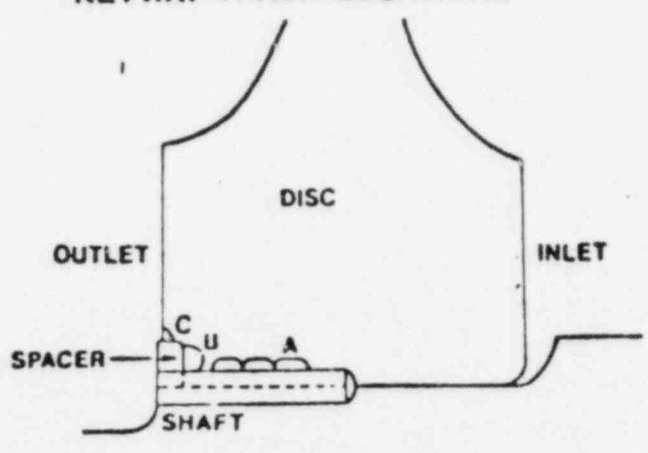


Figure 1

WARREN S. HAZELTON
PROFESSIONAL QUALIFICATIONS

My name is Warren S. Hazelton. In my capacity as Section Leader, Engineering Materials Application Section, in the Division of Engineering, I am responsible for reviewing materials related aspects of operating nuclear power plants. In conjunction with this work, I am also responsible for aiding in the preparation of Federal Regulations and Regulatory Guides relating to materials, inservice inspection, and operational limitations important to the safety of nuclear power plants. Another primary responsibility is reviewing research programs on reactor safety, evaluating results of these programs, making recommendations for new programs, and factoring the results of these programs into our other review activities.

I was born in Cutler, Minnesota on October 20, 1916, and attended public schools in Duluth and Wahkon, Minnesota. After attending the University of Minnesota intermittently, I joined the Armed Services in 1941. I was discharged in 1945 after serving as an Army Air Force Pilot. I then resumed my education at the University of Minnesota, was honored by being selected for "Plumb Bob," and graduated in 1949 with a Bachelor of Metallurgical Engineering degree, with distinction.

From 1949 to 1960, I was employed in the Westinghouse Aviation Gas Turbine Division, at South Philadelphia and at Kansas City, Missouri. From 1954 to 1960, I was manager of the materials application and development activity, responsible for the materials aspect of design, materials properties, failure analysis, and the development of new materials.

From 1960 to 1963 I was Supervising Engineer of the Materials Development Section at the Westinghouse Bettis Atomic Power Laboratory. In this capacity I was responsible for development programs in the fields of stress corrosion, brittle fracture prevention, and radiation damage.

From 1963 until 1972, when I assumed my present position, I held various management positions in the Westinghouse PWR Systems Division. My respnsibilities included the development and application of improved fracture prevention technology, evaluation of radiation damage, stress corrosion prevention, and involved close interface with design groups. I was responsible for the detailed failure analysis performed on the internals at the Yankee Rowe, Connecticut Yankee, Trino (Italy), and SENA (Franco-Belg.) plants. I also participated actively in the redesign and repair work performed for these plants.

I have been active in the preparation of Codes and Standards relating to reactor safety. Specifically, I am a member of several ASME Boiler and Pressure Vessel Code committees, the Pressure Vessel Research Committee Task Group on Fracture Toughness Requirements, and several ASTM committees developing standards for evaluating radiation damage of metals.

CLIFFORD DAVID SELLERS
PRINCIPAL MATERIALS ENGINEER - MATERIALS ENGINEERING BRANCH
DIVISION OF SYSTEMS SAFETY

PROFESSIONAL QUALIFICATIONS

In my present position as Principal Materials Engineer in the Materials Engineering Branch, I am involved in safety review and evaluation of materials used in the construction of nuclear power plants.

The Materials Engineering Branch is responsible for materials application, metallurgical investigative studies, fabrication problems, and inservice degradation processes such as stress corrosion and radiation effects. Other responsibilities of the branch include materials integrity, fracture toughness criteria, inservice inspection requirements, and potential inservice degradation processes such as crack growth, material creep and fracture for the wide range of materials used in the construction of nuclear power plant components. In addition to the normal casework review responsibilities, I have been involved in problems in many of the areas enumerated above.

I have a BS degree in Metallurgy (Penn State 1951) and have done graduate work at the University of Delaware and University of Idaho.

From 1968 to 1973 I was a Senior Engineer with Westinghouse Nuclear Energy Systems-PWR Systems Division in Monroeville, Pennsylvania.

In this position my duties involved design assistance and troubleshooting on reactor internals, control rods and instrumentation, and reactor pressure vessels. These duties and other field problem investigatory activities led to preparation and use of a field metallography lab. In this and other connections, I have been involved in various activities at Beaver Valley, Cook, Zion, Turkey Point, San Onofre, Ginna, Yankee Rowe, Haddam Neck, Indian Point, Salem, and SENA.

During the years 1964 to 1968, I was employed as a Quality Engineer at the Naval Reactors Facility located near Idaho Falls, Idaho and served as site materials engineer. In my capacity of quality assurance engineer I prepared procedures, reviewed procurement documents and performed audits. My major accomplishments were the establishment of materials receiving inspection and a verification program.

From 1961 through 1963 I was a senior metallurgical engineer at the Bettis Atomic Power Laboratory. In this position I was a "cognizant engineer" for various high strength structural alloys such as 17-4 PH; 12% chromium steels; low alloy (bolting) steels; Inconel X; Haynes 25, etc., with responsibility for specification preparation and troubleshooting. Additionally, I was involved in failure analysis of components fabricated from these alloys. I performed field and in-plant inspection of 17-4 PH control rod drive mechanism components. Additionally I was involved in testing of specimens prepared from irradiated components and preparation of irradiation programs on high strength bolting materials.

From graduation in 1951 I was employed in various degrees of increasing responsibility at the Westinghouse Electric Corporation Aviation Gas Turbine Division until that Division's dissolution at the end of 1960. I initially was responsibile for the radiographic inspection of and shop contact on aluminum and magnesium base castings and investment cast refractory alloys and fabrications. Subsequently I was involved in shop contact and troubleshooting of our in-house casting and forging shops. Later I was responsible for development of and applications for improved light-alloy and refractory alloys, including preparation of design data and testing of engine hardware. Near the end of my service with this division I performed extensive failure analysis work on both engine and test rig failure, both in-house and in the field. During this period I received 13 patent disclosure awards and was involved in training of personnel.

In my last year of college and the preceeding summer I worked at Penn State as an undergraduate lab technician in the Metallurgy Department with responsibilities for fabrication, testing, and photography of equipment and specimens and for the metallurgy of test specimens. The project was a joint Metallurgy/Ceramics Department project on the vitreous enameling of steel.