TECHNICAL REPORT ON STEAM GENERATOR CHANNEL HEAD CLADDING

INDIAN POINT UNIT NO. 3

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Report on Steam Generator Channel Head Cladding

SECTION 1 - ABSTRACT

The stainless steel cladding of the Indian Point Unit No. 3 steam generator channel heads contains imperfections which were identified by liquid penetrant examination.

Attempts to remove the imperfections mechanically and restore the cladding were successful in one steam generator, but resulted in increasing the number of indications in the three remaining steam generators.

Studies of cladding samples taken from the channel heads have identified stress corrosion and dilution of the clad deposit with base metal as possible causes for the imperfections. It is Con Edison's opinion that development of imperfections in an excessively diluted clad deposit could have been triggered or extended by a stress corrosion mechanism.

It has been established that the present cladding condition will not compromise the integrity of the channel heads and will not adversely affect operation of the unit.

A surveillance examination program is being developed to verify the prediction that the imperfections will not propagate significantly during the service life of the plant.

SECTION 2 - SUMMARY

The channel heads of the nuclear steam generators at Indian Point No. 3 are carbon steel castings, weld-clad on the inside surface with stainless steel. It is the objective of the cladding to prevent the development of carbon steel corrosion products that would enter the coolant and would be carried throughout the primary system.

In March, 1975, rust colored deposits were noted during a post-hot-functional test visual examination of the steam generator channel head clad surfaces. Subsequent liquid penetrant examination identified imperfections in the cladding. Attempts to remove the imperfections mechanically and restore the cladding, were successful in one steam generator, but resulted in increasing the number of liquid penetrant indications in the three remaining steam generators.

Samples were taken by Westinghouse from representative areas of the cladding and were examined metallurgically. Weldability tests were performed on the cladding in the steam generator channel heads, and additional samples were taken for metallurgical study. To assist in the evaluation of the results of the metallurgical examinations, Con Edison retained a consultant, Dr. Warren F. Savage of Rensselaer Polytechnic Institute. Dr. Savage is recognized for his expertise in the field of welding and weld-cladding.

Based on evaluation of stress analyses, corrosion test data and service experience, it is Con Edison's opinion that the present cladding condition will not compromise the integrity of the channel heads, and will not adversely affect operation of the unit It is also predicted that the imperfections may propagate within the cladding, but will not propagate cracks into the base metal. Therefore, the cladding condition will not have any adverse effects on the service life of the steam generator.

Alternative actions were considered. It is concluded that repair is not required and that cosmetic rework is not desirable. The present cladding condition is considered acceptable.

A study was made of alternative instrumented non-destructive examination procedures which could be used to verify the prediction that the imperfections will not propagate into the base metal. Ultrasonic examination of the channel head from the outside surface appears to be a viable technique. At present time, additional development work is being performed to verify and check accuracy of this technique.

A surveillance program is proposed which will include preservice examination and in-service examination during the first two refueling periods, and subsequent evaluation of the on-going program needs for the remainder of the service life of the plant.

SECTION 3 - INTRODUCTION

3.0 Introduction

The Indian Point Unit No. 3 is a Westinghouse Pressurized Water Reactor having an initial design output of 3025 MW thermal (965 MW, electric). The unit is presently being completed, with core loading and initial criticality being the next major scheduled milestones.

3.1 Reactor Coolant System

The Reactor Coolant System consists of four similar heat transfer loops connected in parallel to the reactor vessel. Each loop contains a steam generator, a pump, loop piping, instrumentation and miscellaneous connections. (Figure 3-1). The pressurizer surge line is connected to loop number four, hot leg.

3.2 Steam Generator

The steam generators are Westinghouse Series "44". They are vertical U-tube natural circulation boilers, designed and manufactured in accordance with Section III (Class A Nuclear Vessels) of the ASME Boiler and Pressure Vessel Code, 1965 Edition with addenda through Summer 1966. Each steam generator is designed to deliver 3,320,000 Lbs/hr. of steam at 770 psia and 514F, which corresponds to the maximum guaranteed (3087 Mw thermal) rating of Indian Point Unit No. 3. Each steam generator consists of three sections, an evaporator section, a steam drum section, and a primary coolant channel head. The evaporator section is a shell and U-tube heat exchanger. The steam drum section houses moisture separation equipment. (Figure 3-2).

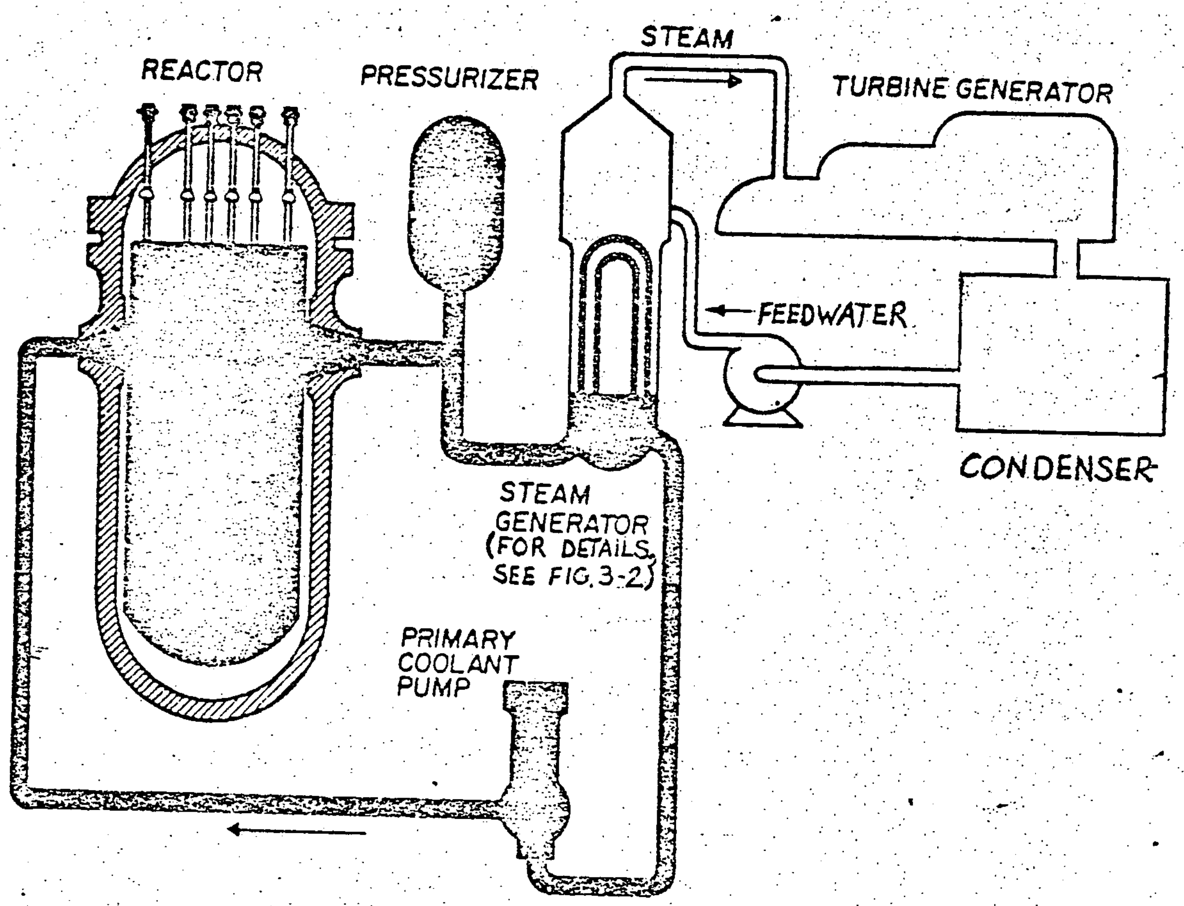


Figure 3-1 - Illustration of a one loop reactor coolant system with reactor

The steam generator is mounted vertically on support pads cast integrally with the channel head.

During service, high temperature, high pressure reactor coolant enters the inlet side of the channel head at the bottom of the steam generator, through the inlet nozzle, flows through the U-tubes to the outlet side of the channel and leaves the generator through the outlet nozzle. The inlet and outlet channels are separated by a partition plate.

On the secondary side, feedwater enters the evaporator section of the steam generator just above the top of the U-tubes through a feedwater ring. The water flows downward through an annulus between the tube wrapper and the shell and then upward through the tube bundle where a portion of the water is converted to steam. The steam-water mixture form the tube bundle passes through a series of moisture separators which dry the steam for delivery to the turbine. The moisture removed from the steam is returned to the evaporator section.

An access opening (manway) for inspection and maintenance is provided in each half of the channel head. The upper shell (steam drum section) has two access openings for inspection and maintenance of the dryers. Two smaller access openings (handholes) in the lower shell permit inspection of the shell side of the tube sheet.

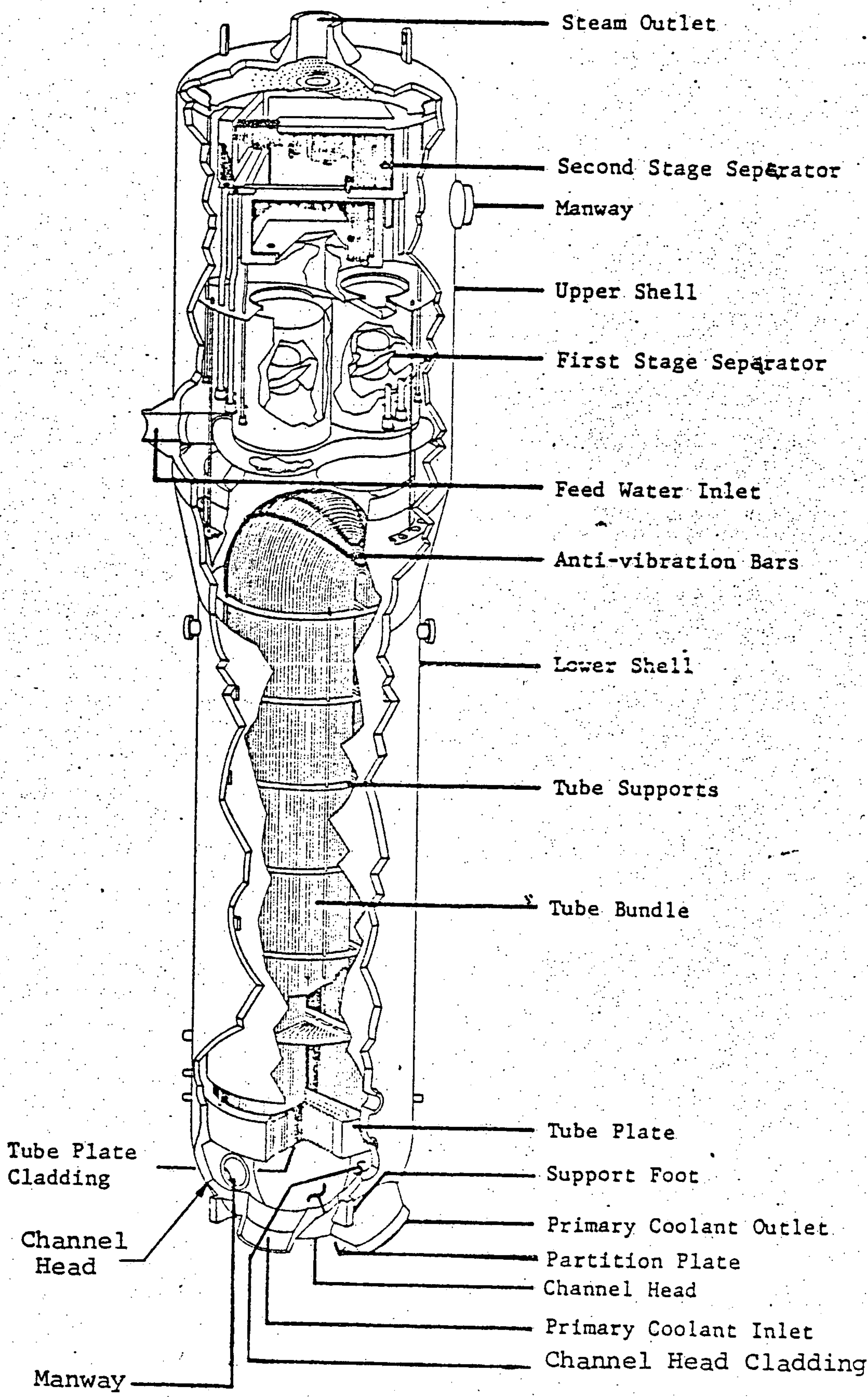


Figure 3-2 - Steam Generator

The shell of the Indian Point Unit No. 3 steam generators is constructed of manganese-molybdenum steel (ASME SA 533, Grade A, Class I) plate. The heat transfer tubes are Inconel (ASME SB 163). The tube sheet is manganese-molybdenum steel (ASME SA 508 Class II) and the channel side of the tube sheet is clad with Inconel.

The channel heads of the steam generators are carbon steel castings, (ASME SA 216, Grade WCC). The interior surfaces of the channel head are weld clad with austenitic stainless steel. The cladding is a series submerged arc weld overlay using 309 stainless steel weld metal, (ASME SFA 5.9, Class ER 309). The Westinghouse specification for the weld metal, designed to assure proper ferrite control, is:

Nickel:	12.00% - 13.00%
Chromium.	min.: 11.00% + % Nickel; max.: 25.00%

An outline drawing of the channel head is presented in Figure 3-3.

3.3 Channel Head Fabrication for Indian Point Unit No. 3

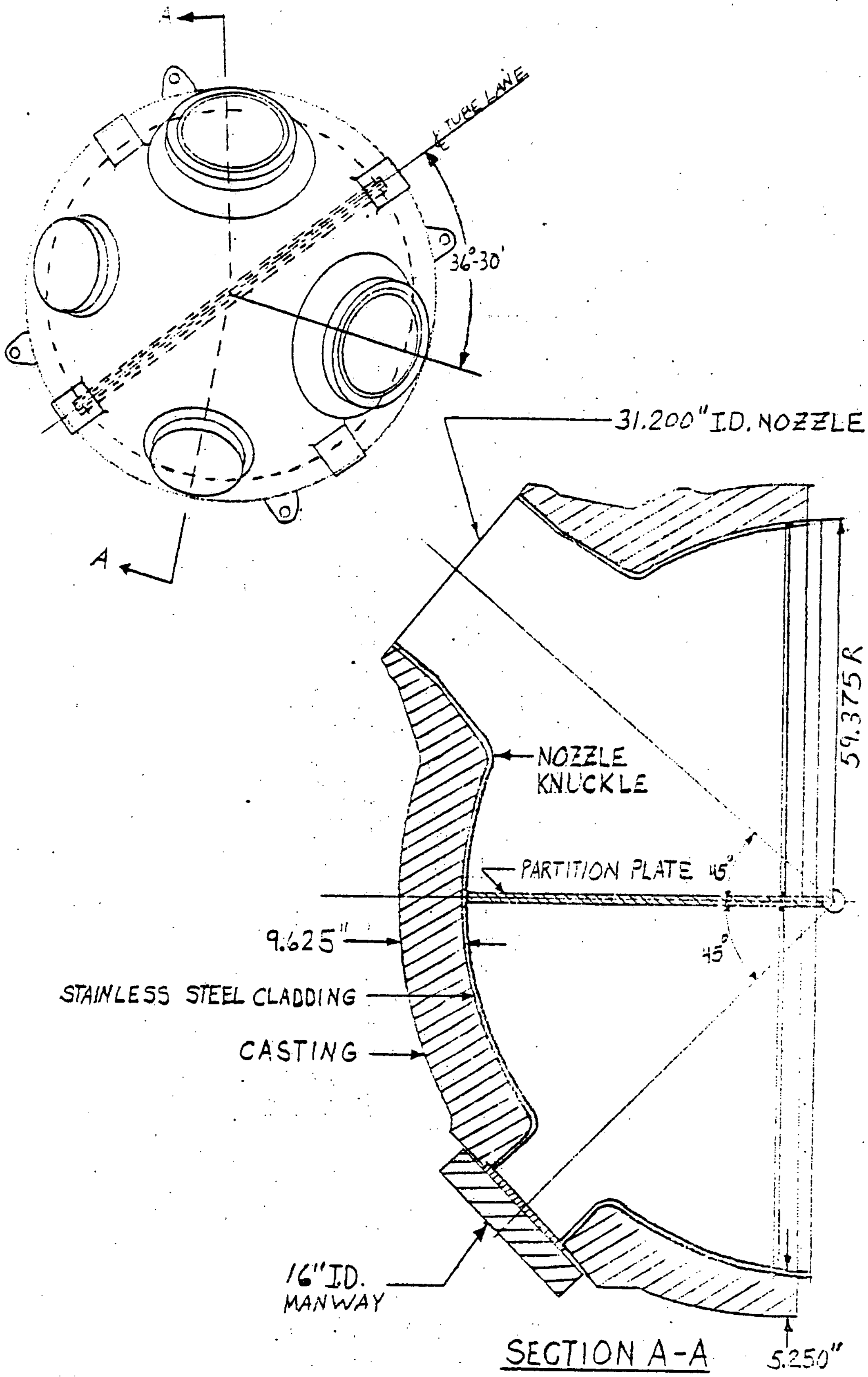
The four steam generators at Consolidated Edison's Indian Point Unit No. 3 plant were initially fabricated at the Westinghouse Lester (Penna) Heat Transfer Division.

During fabrication of the steam generators, the channel head cladding was liquid penetrant examined by Westinghouse after deposit and after post weld heat treatment. The channel head cladding was exposed to two post-weld heat treatments during fabrication; the first post-weld heat treatment occurred after cladding and the second occurred after joining the channel head to the tube plate. A liquid penetrant examination was performed on the cladding within the heat affected areas subsequent to the channel head/tube sheet joint post-weld heat treatment.

The lower shell of each steam generator, as completed at Lester, included tubing, weld overlay of the channel heads and joining of the heads to the lower shell. Upper shell assemblies were also completed at Lester, and the mating parts were shipped by barge to the Tampa (Florida) Division for the final closure weld at the cone of the upper shell.

During the barge transfer, sea water leaked into the mechanically sealed nozzles and contaminated the channel head cladding. After arrival at Tampa, the sea water intrusion was detected and a flushing operation was performed until no chloride ions were detected on cleaned, washed surfaces within the primary side of the steam generator. At Tampa, the lower shell was welded to the upper shell, completing the fabrication of the steam generator. Prior to shipping the completed steam generators to the site, a cleanliness verification examination of the primary side was made and the units were closed with welded shipping covers to preclude the possibility of sea water re-entering while in transit to the Indian Point site. The steam generators were then shipped to Indian Point.

REVISIONS



SECTION A-A

STATION- INDIAN POINT UNIT No. 3 STEAM GENERATOR COOLANT CHANNEL HEAD	APPROVALS	SUB-SECT. ENGR.	Con Edison FIG. 3-3
DRAWN BY J. J. HUZA		ENG. S. ROTHSTEIN	ENGINEERING SKETCH No.
SCALE NONE ESM/ESR No.		DATE 8-26-75	PAGE 3-7

After placement of the steam generators into the containment, Westinghouse repaired the divider plate to tube sheet joint. This repair required removal of the explosively bonded cladding between the tube sheet and the divider plate, replacing it with overlay weld cladding and post weld heat treating at approximately 1100-1150F. The repair was completed by rejoining the divider plate to the restored tube sheet cladding. (Footnote 1).

1) Report on Steam Generator Tubesheet Cladding, Docket No. 50-247,1972)

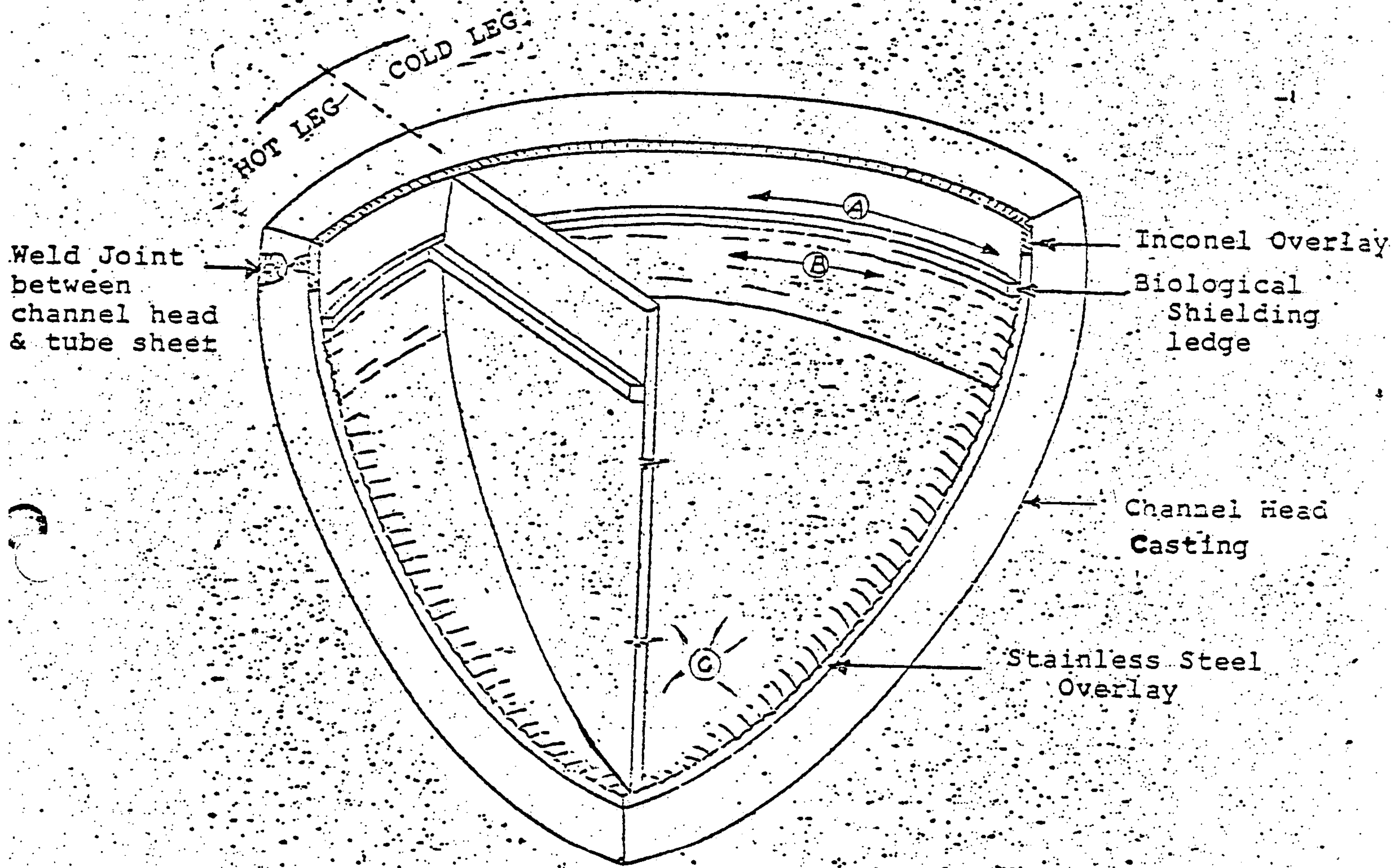
SECTION 4 - HISTORY OF CLADDING CONDITION OF INDIAN POINT UNIT NO. 3 STEAM GENERATORS

4.1 Initial Identification of Imperfections

In March 1975, following hot functional testing of the plant, rust colored deposits were noted on the clad surface of the channel head in steam generator 31 outlet water-box. The rust colored deposits were near the biological shielding ledge (Figure 4-1). Liquid penetrant examination performed in these areas revealed linear indications oriented parallel to the weld beads.

The liquid penetrant indications were explored on an investigative basis and in one case excavated to a depth exposing base metal. Similar liquid penetrant indications were found in steam generator 32, and visual examination revealed superficial stains in varying degrees on clad surfaces in all steam generators.

Because of the previous history of the steam generators' exposure to sea water, it was decided to liquid penetrant examine all primary clad surfaces in each steam generator. This examination detected indications on the cladding of each channel head varying in degree and location. The frequency of indications was highest at the area just above and below the biological shielding ledge. Liquid penetrant indications were detected in isolated areas in each steam generator, with only a minor portion (estimated 5%) of all clad surfaces being affected.



A-- Areas above shielding ledge
B - Areas below shielding ledge
C -"Bowl" area

Typical Areas Containing Liquid Penetrant Indications

Fig. 4 -1

4.2 Initial Repair

Systematic removal of the clad indications was initiated concurrently in all steam generators.

Indications were removed by local grinding and polishing. In some instances, it was necessary to excavate until the carbon steel base metal was exposed. Areas reworked were then re-examined by liquid penetrant.

Clad repairs were performed utilizing one of two welding techniques. (1) In areas where carbon steel had been exposed, the cladding was manually restored using the temperbead repair technique. (2) In areas where carbon steel had not been exposed, the cladding was restored by conventional manual weld overlay, without preheat or post-weld heat.

To varying degrees, new indications were detected in the original overlay, after weld repairs were made.

In one instance the cladding was restored at the bottom of the channel head ("bowl") of steam generator #34. Subsequent liquid penetrant examination showed the newly deposited weld metal to be indication-free but adjacent areas (previously indication free by liquid-penetrant examination) exhibited new indications.

In another instance, after totally removing liquid penetrant indications, cladding was restored utilizing the temperbead technique. It was necessary to preheat more than the area required in order to maintain the 400F temperature required for this procedure. Liquid penetrant examination subsequent to this weld repair showed new cladding indications in adjacent areas as far removed as 30 inches away.

Similar patterns were detected in steam generator #31 where temper-bead repairs had been utilized. Areas which had been locally heated to the required 400F preheat and post-weld heat treated, exhibited new clad indications.

4.3 Sampling

Metallurgical specimens (boat samples) were removed from the channel head clad surfaces and forwarded to Westinghouse laboratories at Tampa and Pittsburgh for examination and evaluation. Samples were removed from areas having a high incidence of clad indications and from areas previously known to have been exposed to sea water. Also, a series of weldability tests was performed and samples were removed for metallurgical analysis.

4.4 Summary of Present Condition

At this point, all cladding indications whether partially or totally removed were mapped and documented. It is estimated that the surface area now exhibiting dye penetrant indications had been increased two-fold, and comprised approximately 10% of the total channel surface.

4.5 Evaluation of Present Condition

The Indian Point Unit No. 3 proposed Inservice Inspection Program (Footnote 2) has been based on ASME B & PV Code Section XI, 1970 Edition. Paragraphs IS 251 and IS 261 of Section XI require that at least one patch (36 square inches of cladding) near each manway in the primary side of the vessel be visually examined pre-service and at or near the end of each inspection interval. Paragraph IS 311 stipulates that evaluation shall be made at any indications which exceed the acceptance standards for materials and welds specified in the ASME B & PV Code, Section III, Nuclear Vessels, to determine disposition and/or the need to make repairs. Section XI (Foreword) stipulates that "In the event that repair or replacement is required, the intent of this Section of the Code is that restoration should be governed by the original acceptance standards". In this case, ASME B & PV Code, Section III, 1965 edition plus addenda through Summer 1966, provides the bases for the original acceptance standards. The applicable edition of Section III does not require liquid penetrant examination of the cladding. Paragraph N-320 of the applicable edition of Section III specifies that cladding may be repaired by welding provided the defects are removed and the resultant surfaces examined by the liquid penetrant method prior to welding.

Based on the above, inasmuch as penetrant examination is not required, the cladding can be considered acceptable under the applicable code.

2) Item 3.7 of Section 4.2 of Proposed Technical Specification (FSAR Section 15).

Furthermore, the 1974 edition of the ASME B & PV Code Section XI and its addenda provide additional guidance in evaluating the acceptability of the imperfections in the cladding.

In their May, 1975 meeting, the Code Subcommittee on Inservice Inspection adopted changes to the acceptance standards for surface indications in austenitic cladding on piping. These changes stipulated that inner surface indications which 1) are detected by volumetric examination of piping components with austenitic cladding on the inner surface and 2) do not penetrate through the nominal clad thickness into base metal, are acceptable and need not be compared with the standards of IWB 3514.1 (a) (i.e. which defines the sizes of allowable planar indications). These changes have been accepted for publication in the Winter 1975 Addenda to Section XI.

In their August, 1975 meeting, the Code Subcommittee on Inservice Inspection proposed changes to the acceptance standards for surface indications within the cladding on nozzle inner surfaces and adjacent areas. These changes stipulate that the size of allowable surface indications detected within cladding shall be governed by the following standards:

1. Inner surface indications not penetrating into base material are acceptable except for nozzle inner corner radius indications.
2. Inner surface indications at other than the inner corner radius of a nozzle, that penetrate through the cladding into the base metal shall not exceed

the limits of IWB 3512.1 (a) except that the depth "a" of the indication shall be total depth minus the clad thickness. (Note: Application of this provision to pre-service inspection of the biological shielding ledge area of the channel head would define as acceptable an infinitely long planar indication 0.1" deep.)

It is technically sound to apply the same criterion to cladding indications in a steam generator channel head, as is applied to the general inner surface of nozzles.

There are no indications of cladding cracks at the inner corner radius areas of the nozzles on the Indian Point Unit No. 3 steam generators and there are no cracks extending into the channel head base metal of the Indian Point Unit No. 3 steam generators.

On this basis, the present cladding in the Indian Point No. 3 steam generator channel heads should continue to be acceptable under the currently proposed addenda to Section XI.

SECTION 5 - METALLURGICAL ANALYSES OF CLADDING

5.1 Studies

5.1.1 Methods of Analysis

The following metallurgical analysis methods were employed to study samples returned for evaluation.

1. Macro and light microscopic examination
2. Electron microprobe analyses.
3. Scanning Electron Microscopy (SEM) incorporating energy dispersive analyses of the X-ray spectra (EDAX) generated by the SEM.
4. Transmission Electron Microscopy (TEM) incorporating electron diffraction analysis.
5. Chemical Analyses

5.1.2 Macro and Micro Examination

The fracture faces appear to be typical of intergranular and interdendritic fracture. Some discontinuities originate in pits at the clad surface and follow the grain pattern interdendritically normal to the surface. Many discontinuities originate in the heat affected zone of the previously deposited bead where the solution annealing effect of the heat of welding has put much of the original ferrite in solution.

Metallographic examination revealed normal microstructure, consisting of austenite plus ferrite.

Generally, the presence of discontinuities is a function of the ferrite morphology. Specifically, the discontinuities are essentially non-existent in areas containing high ferrite, are less pronounced in areas of intermediate ferrite, and are most prevalent in predominantly low ferrite heat affected zones. There also appeared to be thin (less than 1 micron thick) grain boundary films.

5.1.3 Scanning Electron Microscopy

Scanning electron microscopic examination of several of the "broken open" surfaces of a boat sample showed the fracture surfaces to be intergranular and a mixture of inter and transdendritic fracture.

Energy Dispersive Analysis by X-rays (EDAX) of fracture surfaces indicated the presence of chloride in a small number of instances. Foreign particles were found on the "broken open" fracture faces of one of the boat samples indicating that these particles were present in the discontinuities of the sample taken from the cladding. EDAX analysis of the particles indicated the presence of sodium, potassium and chlorine. These elements are found in sea water; however, there is no report of calcium or magnesium, which would be expected in sea-water residues.

5.1.4 Electron Microprobe Analyses

A quantitative microprobe analysis was made. It was found that the as-deposited cladding contains normal percentages of chromium and nickel within the bead as well as in the heat affected zone.

In addition, the discontinuities were probed for presence of lead, tin, chlorine, mercury and sulfur, with the results shown below.

Element	Quantity
Chlorine	Trace
Lead	Undetectable
Mercury	Undetectable
Sulfur	Trace
Tin	Undetectable

The above results indicate the absence of minor elements which cause hot short cracking (except sulfur) and the presence of chlorine and sulfur which are common to sea water.

5.1.5 Transmission Electron Microscopy Including Electron Diffraction Analysis

After normal replica processing, typical areas were viewed on the transmission electron microscope and an electron diffraction pattern of the deposits was generated. It was determined that Fe_3O_4 is the main constituent on the fracture face, although the possibility of some Fe_2O_3 does exist. The following oxides were not present.

FeO	(iron oxide)
NiO	(nickel oxide)
Ni_2O_3	(nickel oxide)
CrO	(chromium oxide)
Cr_2O_3	(chromium oxide)

5.1.6 Chemical Analyses

The results of chemical analysis of two boat samples were as follows:

Sample	C	Mn	P	S	Si	Ni	Cr
1	-	-		-	-	7.7%	17.7%
2	.103	1.27	.02	.012	.50	7.73%	16.5%
Ave						7.72%	17.1%

When compared to the microprobe chemistry, there is good agreement on nickel content but an approximately 2% difference in chromium content. (Microprobe analyses are considered accurate within 5%). Schaeffler diagram calculations using the higher chromium content indicate ferrite in the range observed metallographically. Calculations using chromium determined by X-ray emission spectroscopy would indicate 3- 4% lower ferrite than observed metallographically. Therefore the results of chemical analyses are in agreement with the observed microstructure.

5.1.7 Auger Spectrometic Analyses

Auger spectrometric analysis of a fracture face of a sample fractured in vacuum indicated the presence of iron, nickel, chromium, oxygen and carbon, and the complete absence of calcium, silicon, aluminum, magnesium, sodium and chlorine.

This analysis reduces the probability that either chloride stress corrosion or an intergranular silicate film are significant causative agents for the condition of the steam generator channel head cladding.

5.1.8 Weldability Tests

Weldability tests were performed on the cladding, and boat samples were taken for evaluation of the deposit, wet chemical analysis and X-ray emission spectrographic analyses. Three different tests were employed to determine weldability:

1. A shielded metal arc weld pad was deposited near the bottom of the bowl in steam generator No. 34 primary coolant inlet water-box.
2. An area in the primary coolant outlet water-box encompassing the same beads as 1, was re-fused by gas tungsten arc welding and a circular patch without filler was fused similarly on this area to simulate a circular patch crack sensitivity test.
3. Three radial shielded metal arc weld stringers were made in the primary coolant inlet and outlet water-boxes of steam generators Nos. 31, 32, and 34. These stringers started at the bottom of the bowl and extended upward approximately 50". In each water box, one weld stringer bead was deposited between the partition plate and the nozzle, one between the nozzle and the manway, and one between the manway and partition plate.

No clear cause for the cladding cracks is discernible from the optical metallographic examination of the samples taken from 1, above.

The weldability test 2, above, demonstrated that the basic weld clad chemistry was satisfactory, and that it could be remelted with a tungsten arc torch without cracking or fissuring.

No cracking or fissuring was observed in the re-fused area or re-fused circular patch. Beneath the re-fusing, however, discontinuities were observed which stopped or were "sealed" at the fusion line, indicating that the chemistry of the clad deposit was basically sound.

An additional boat sample of original clad was liquid penetrant examined and examined metallographically; no defects were found. A gas-tungsten arc weld pass was made on the sample; again, no defects could be detected either in the re-fused weld or the clad underneath. A bend test was then made on this sample; no defects were found. Based on metallographic examination, all samples contained approximately 6 - 8% ferrite generally, but interbead heat affected zones contained less ferrite.

No imperfections were observed in the weldability test beads of test 3 above, but numerous imperfections developed in adjacent original cladding. The "radial bead" crack sensitivity test indicated interbead "tie-ins" are susceptible to the development of imperfections during repair welding.

5.2 Probable Cause of Imperfections

5.2.1 Dilution of Cladding with Base Metal

When carbon steel is clad with another alloy by welding, it is anticipated that some dilution of the weld deposit with the base metal will occur. Therefore, the filler metal selected is one which contains an alloy content greater than that desired in the cladding. For stainless steel cladding on carbon steel, filler wire E 309 is frequently the choice, and a dilution of approximately 15 to 20% is normally anticipated.

The alloy content of the Indian Point Unit No. 3 steam generator cladding, the base metal and the filler wire is summarized in Table 5-1.

Table 5-1
Alloy Content of Cladding & Materials Used

Material	Chromium	Nickel	Carbon	Reference
Cladding	19.3	7.3	-	Microprobe
Cladding	17.06	7.72	.103	Wet chemistry
Filler Wire (E309)	24.88	13.81	.019	Westinghouse/Techalloy (used on S.G. 31, 33, 34)
Filler Wire (E309)	24.14	12.98	.025	Westinghouse/Techalloy (used on S.G. 32)
Base Metal	0.12	0.36	0.19	General Electric (S.G. 32)
Base Metal	0.10	0.37	0.22	General Steel (S.G. 31)
Base Metal	0.14	0.09	0.25	General Steel (S.G. 34)

Comparison of the nickel content in the cladding with the nickel content of the materials that make-up the cladding (the base metal and the filler wire) indicates that the cladding is equivalent to the filler wire diluted 45% with base metal. A similar comparison of the chromium content indicates that the cladding is diluted 25 to 30%. It should be noted that these are average conditions. Although it is generally accepted practice to accept chemical analyses as representative of a casting or weld deposit, it is recognized that castings and weld deposits can vary locally in chemical composition.

Referring to the Schaeffler constitutional diagram, Figure 5-1, it is apparent that the cladding falls into a region where austenite, ferrite and martensite may be present. Local variation in alloy content of the cladding plus variations in the cooling rate and the reheat temperature of the heat affected zone of each deposited bead account for the wide variation in ferrite content noted in magnagage readings, as well as the variation in structure noted in the boat samples. Small differences in unit heat input resulting from changes in weld parameters such as arc voltage, distance between arc and base metal, and rate of travel would result in variations in the chemical composition and consequently in the metallurgical structure of the cladding. Areas low in ferrite would be subject to microfissuring; high ferrite would be reasonably ductile. Variations in martensite content would also result in variations in hardness and ductility.

Given the average dilution that chemical analyses indicate had occurred, small variations could explain the facts that imperfections develop in some weld beads but not in others, and that some areas of weld deposit appear to be less ductile than others.

5.2.2 Grain Boundary Effects

Metallographic examination of boat samples has indicated that the discontinuities are intergranular and predominantly interdendritic. Many discontinuities appeared to contain a gray constituent and some sections exhibited a dark-etching feather-like structure similar to bainite or martensite. If martensite did form, as the constitutional diagram indicates possible, it would probably do

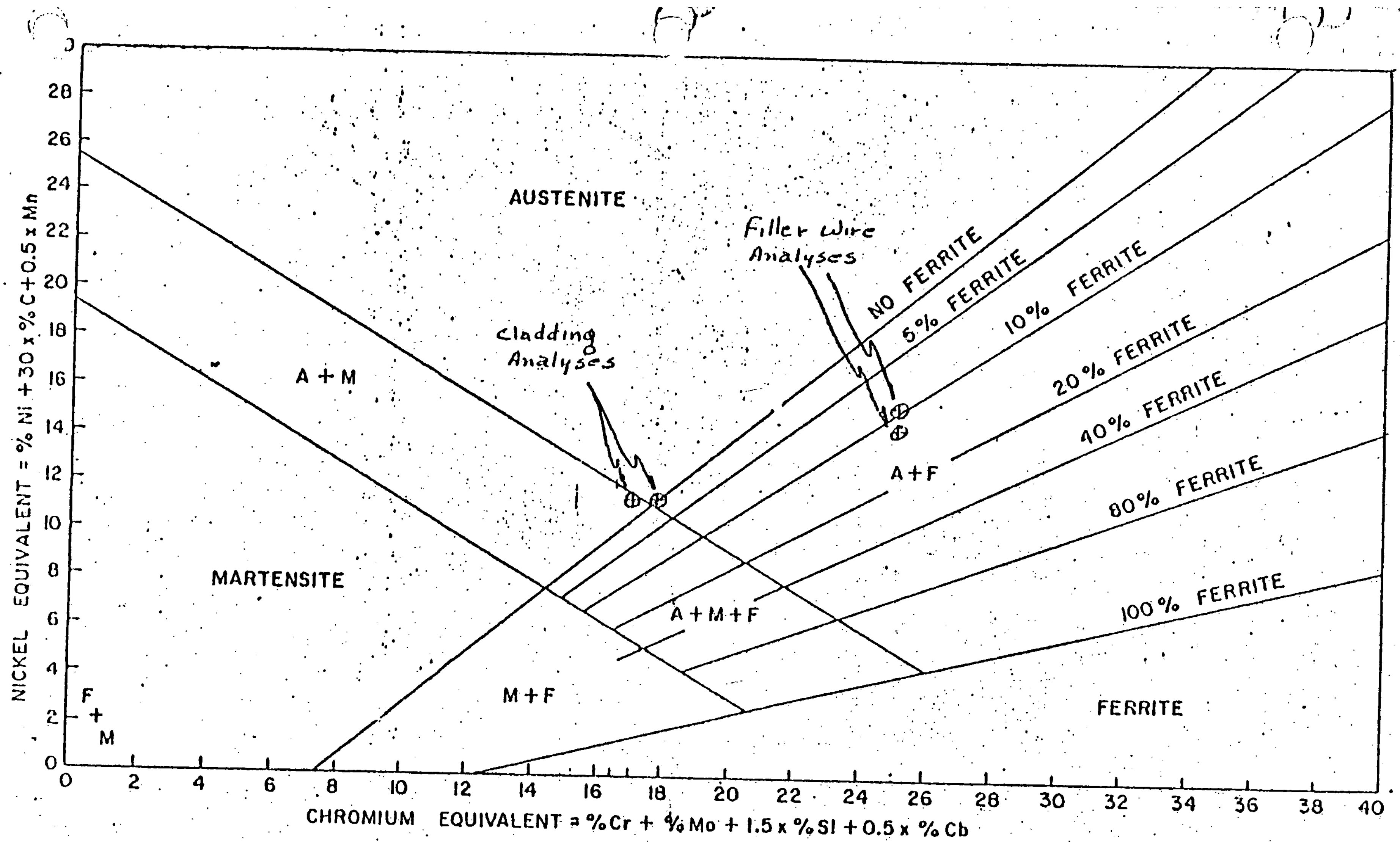


FIG. 5-1 SHAEFFLER DIAGRAM

so at the solidification grain boundaries where carbon and those alloys which increase the hardenability would be likely to segregate. This would result in a grain boundary constituent that is low in ductility, and could explain the propagation of imperfections during the reworking effort.

The low values for sulfur and phosphorus reported in the wet chemical analyses,and the absence of silicon on the fracture face reported in the Auger spectrometric analysis reduce the probability of significant non-metallic formations at the grain boundaries, and eliminate completely the possibility that the weld deposit was hot short.

5.2.3 Stress Corrosion

Study of the results of various examinations, history of the units, and the literature on welding defects and corrosion processes in cast austenitic steels does not clearly permit the identification of the imperfections in the channel head cladding as exclusively related to weld metal properties, or to a corrosion process, or to some combination of both.

It is generally reported that cast stainless steels are at least as resistant and probably more resistant to chloride stress-corrosion than are the wrought materials. Wrought type 304 stainless steel is not cracked by chlorides at room temperature unless hydrochloric acid is present. (Footnotes 3, 4, 5). In seawater, observations on stressed Erichsen cup specimens of 304 stainless steel showed no stress-corrosion cracking in 2 year exposure to raw seawater at temperatures of 114-125F, although severe pitting occurred (Footnote 6).

At ambient temperature, in the presence of sea water, any corrosion in weld overlays would most likely be of the pitting type (as was detected) rather than stress corrosion.

An increase in the resistance of cast material as compared to that of wrought material was reported in tests in 875 ppm NaCl at 400F (Footnote 7), where cracking was observed to propagate through the austenite and around the ferrite. Flowers, et al., attributed the increased resistance to cracking of the cast material to a "keying" action of the ferrite.

Under ordinary circumstances, no corrosion would be expected during a post weld heat treatment. The results of the metallographic examination wherein attack was seen to be related to ferrite content

3) S.J. Acello and N.D. Greene, Corrosion 18, 286 (1962).
4) R.W. Staehle, "Theory of Stress Corrosion Cracking in Alloys", edited by J.C. Scully
5) G. Binachi, F. Massa, and S. Torchio, Corrosion Science 13, 165 (1973).
6) R.T. Jones, Metals Engineering Quarterly, 7, No. 3, p. 37 (August 1967).
7) J.W. Flowers, F.H. Beck, and M.G. Fontana, Corrosion 19, 186t (1963).

would indicate the possibility of a stress corrosion failure following the pattern shown by Ishihara, et al. (Footnote 8) Interdendritic caustic stress corrosion cracking was consistently observed by Hart in KOH coated samples of three alloys exposed to 300C steam. (Footnote 9) Hart further showed that sulfur-bearing species plus steam led to reproducible interdendritic stress-corrosion cracking. Additionally, Hart showed interdendritic attack in steam at 100C and 300C on samples of all three alloys which had been pre-sulfided by being heated at 400C in an H2S atmosphere.

Clad indications at Indian Point are predominately located in two distinct areas, 1) in the area of the biological shield ledge and 2) in the bottom of the bowl in a radius of 30-40" from center. This suggests that a contaminant other than sea water may have been present after the steam generators were placed in the vertical position. However, no such contaminant has been identified by the metallurgical studies.

The degree of significance of the environments described in the papers cited to actual conditions in the Indian Point Unit No. 3 steam generators is indeterminate. These references show that interdendritic stress corrosion processes

8) Ishihara, T., Shimizu, Y., and Ito, G., "Stress Corrosion Cracking of Austenitic Stainless Steel Overlays in High Temperature Water," Welding Research Abroad, Vol. XXI, 4, April 1975, pp. 11-18.

9) A.C. Hart, British Corrosion U., 6, 165 (1971)

are possible in cast microstructures of austenitic stainless steel, but they leave open the question of the pertinence of observations to the present clad condition, both in terms of the composition of the 309 weld metal vs. the compositions which have been studied, and also in terms of the environments which produced pitting or cracking. Controlled experiments on the stress corrosion characteristics of 309 weld metal in chloride environments are not extensive enough to be related unambiguously to the cladding condition.

5.3 Prognosis

5.3.1 Propagation of Discontinuities in Cladding

Metallographic studies have indicated that the cladding grain boundaries appear not to be ductile. Although no micro-fissures were seen, the analysis of the clad deposit and its resultant microstructure would make it possible that micro-fissures do exist. It is, in fact, postulated that micro-fissures may have served as points of initiation of the imperfections developed during rework. Therefore it is necessary to examine the stresses in the cladding and to evaluate the probability of propagation of existing imperfections or the development of new ones during the service life of the steam generators.

Regardless of the residual stresses in the cladding as a result of deposition and cooling, the residual stresses remaining after stress relief probably do not exceed the yield strength of the base metal at the stress relief temperature. During the cooling of the cladding and base metal after stress relief, a new residual stress pattern develops as a result of the difference in expansion coefficient of the stainless steel clad as compared to that of the carbon steel base metal. (This is discussed in detail in Sub-section 6.1.) This results in a residual tensile stress in the cladding and a residual compressive stress in the base metal, both of the order of the yield strength of the base metal at room temperature. On reheating to the operating temperature of 600F, most of the residual stress is relieved, again because of the differences in the expansion coefficients. However, thermal gradients across the vessel wall result during warm-up, the inside surfaces of the vessel being in compression. As pressure on the coolant is increased, pressure stresses on the vessel wall become a major factor. On cooldown, the cycle is reversed, and when the steam generator is cold, the original post stress relief residual stress pattern is restored.

It is concluded that the cycles of thermal stresses, which developed during stress relief, preheat and post-weld heat treatment, are responsible for the imperfections that have been identified. The imperfections themselves serve as a stress relieving mechanism, and the stresses in the remainder of the cladding resulting from the difference in thermal coefficients are thereby reduced. Furthermore, it is probable that those grain boundaries that are the least ductile are the ones which already have developed into imperfections. Consequently, although it is anticipated that additional imperfections may develop during cooldown periods, it is anticipated that the rate of formation and propagation will be insignificant.

5.3.2 Propagation of Discontinuities in Base Metal

In the course of the attempt to remove some imperfections by grinding away the cladding, it was established that some imperfections extend to, but not into, the base metal. This was further corroborated in the evaluation of the boat samples taken from the steam generator channel heads. Examination and evaluation of conditions at the base metal/cladding interface indicate low probability of propagation of existing imperfections into the base metal during the service life of the steam generators. (This is discussed in detail in Sub-section 6.1.)

5.3.2.1 Propagation by Corrosion

Where the cladding discontinuities extend to the base metal, the base metal at the root of the discontinuity, could be exposed to the general steam generator channel environments.

The environments to which the steam generator channel will be exposed during its service life are summarized in Table 5-2. During normal operation and during short term outages, the environment is not particularly aggressive as the oxygen is held to less than 0.1 ppm. For example, a corrosion rate of 0.24 mils/year was reported for ASME SA302B, (a wrought carbon steel chemically similar to the ASME SA216WCC channel) in a deaerated boric acid solution of 2500 ppm. at 500F. Further details are given in sub-section 6.2.

During extended outages, the environment becomes more aggressive because of the larger concentrations of oxygen. However, the temperature is low. A corrosion rate of 0.6 mil per month was reported for ASTM A302B in aerated boric acid solution of 2500 ppm and pH 4.8 at 100F. Galvanic couples were included in these tests, but there was no difference in the rates of corrosion. Further details are given in Sub-section 6.2.

Assuming the unit is in service 80% of the time, and assuming the corrosion rates above apply to periods of normal operation and to outages, the total corrosion experienced in 40 years of operation in any exposed carbon steel would be of the order of 0.075". It is anticipated that actual corrosion would probably be less than this amount because during much of the off-duty time the primary system would not be opened, and the lower corrosion rate of 0.24 mils/year should apply.

It is recognized that any discontinuity in the cladding would have a sharp leading edge, and it is further recognized that the cladding discontinuity is at a cladding grain boundary which is probably coincident with the grain boundaries of the base metal. If the corrosion described above should occur, it would result in a generalized attack of the base metal at the root of the discontinuity, resulting in a pitting of the base metal at the interface. Rounded pitting would reduce stress concentrations at the base metal/cladding discontinuity interface.

Table 5-2

Indian Point 3, Primary Water Chemistry
(Water in Contact with Stainless Steel Cladding on Steam Generator Head)

Normal Operation

The bulk water chemistry is currently planned to be as follows, when Unit #3 is in operation:

Boron	-	0 to 1000 ppm
Li	-	0.2 to 2 ppm
H_2	-	20 to 40 c.c./kg (STP)
pH_{25C}	-	4.2 to 10.5
Chloride	-	0.15 ppm max
Fluoride	-	0.15 ppm max
Oxygen	-	0.10 ppm max

Short Term Outages

During outages when the primary system is not opened but work is done with auxiliary equipment the above conditions prevail but the hydrogen may be displaced with nitrogen.

Steam Generator Inspection & Maintenance Outages

During outages when the primary system is partially drained, the steam generator cladding surfaces are exposed to humid air. When the unit is filled, air is displaced by water and nitrogen is added. Residual oxygen is removed by the addition of hydrazine. Finally, hydrogen displaces the nitrogen.

Refueling Outages

During an outage for refueling the water contains maximum boron, the impurity limitations are in effect except for oxygen. The dissolved oxygen content is saturated at the ambient temperature. (The first refueling will occur after approximately 30 months of service. Subsequent refuelings will occur at approximately 12 - 16 month intervals)

5.3.2.2 Propagation by Stress

In the metallurgical analysis of the cladding, it was established that there appeared to be low ductility of the cladding grain boundaries. It is known that this condition does not exist in the channel head castings. The channel heads are castings per Grade WCC of ASME Specification SA216 "Carbon-Steel Castings Suitable for Fusion Welding for High Temperature Service". The tensile properties reported for each of the channel heads at Indian Point Unit No. 3 are well above the minima required by the specification. The percentages elongation and reduction of area in all cases are far in excess of the minimum required, and demonstrate more than adequate ductility of the cast metal. Furthermore, a supplementary requirement of specification SA216 is that a specimen 1"x1/2" in section be bent through an angle of 90° about a radius equal to the test specimen thickness without cracking on the outside of the bent portion. Foundry reports of the channel head castings indicate that all castings passed this test satisfactorily. This is further evidence that the castings are sufficiently ductile.

It is most improbable, then, that imperfections such as identified in the cladding will develop in the base metal as a result of design service stresses.

The residual stresses in the cladding and in the base metal immediately below the cladding were discussed above (Par. 5.3.1), and are discussed in detail in Section 6.1.

The base metal surface, at room temperature, probably has a residual compressive stress of the order of the yield strength of the material. During normal service, as a result of the pressure stresses on the head, and the differences in expansion coefficients between it and the cladding, the residual compressive stress changes to an imposed tensile stress.

However, this tensile stress is equal to or less than the conservative design values, so that the probability of discontinuities developing in the base metal as result of service stresses is nil. During outages, when the system is cooled down and the coolant pressure is reduced, the original residual stress pattern is restored. The result is that when the environment could be most aggressive, the base metal surface is in a state of compressive stress, making a stress corrosion cracking mechanism improbable.

5.3.3 Effects on Operating Conditions

It has been stated above that the prime function of the stainless steel cladding is to keep the coolant free from corrosion products of the carbon steel channel head. It is recognized that where the cladding is discontinuous down to the base metal some corrosion of the base metal will occur, and some corrosion product could be released to the coolant.

This must be considered because although the total amount of corrosion product would be small, its presence could be accentuated by radioactivation. Normally, corrosion products generated within the coolant system are released to the coolant, where they are removed ultimately by the purification exchanger in the chemical and volume control system. Corrosion products not removed by the chemical and volume control system can form an out-of-core radioactive corrosion film which is important to the nuclear plant operator in that this film affects normal maintenance practices on plant components. Personnel access to radioactive areas is controlled and the maintenance procedures are carefully planned and monitored to accomplish the required work with the maximum efficiency and in the minimum time. The experience to date on this point has been good, and one result has been the development of improved maintenance procedures and techniques.

The interior surface of the channel head is normally an "as-welded" surface by reason of the method used to provide the cladding. The relatively irregular surface will normally trap some residue of corrosion product and crud. Practically all the indications now in the steam generator channel heads are made evident only by liquid penetrant examinations, and are too tight to be detected visually. During the service life of the steam generator, it is not anticipated that the indications will widen appreciably. The radiation fields in the steam generator channel heads are not expected to be significantly different from fields normally experienced in the steam generator channel heads with equivalent service. Consequently maintenance problems will be caused by surface irregularities at the indications.

SECTION 6.0 - EVALUATION OF INTEGRITY OF HEAD

6.1 Stress Analysis

Paragraph N-444 of the applicable ASME Boiler and Pressure Vessel Code Section III specifies that no structural strength shall be attributed to the cladding except where bearing stress is involved. Further, when the nominal thickness of the cladding is 10 per cent or less of the total nominal thickness of the component, the presence of the cladding may be completely neglected in the stress evaluation.

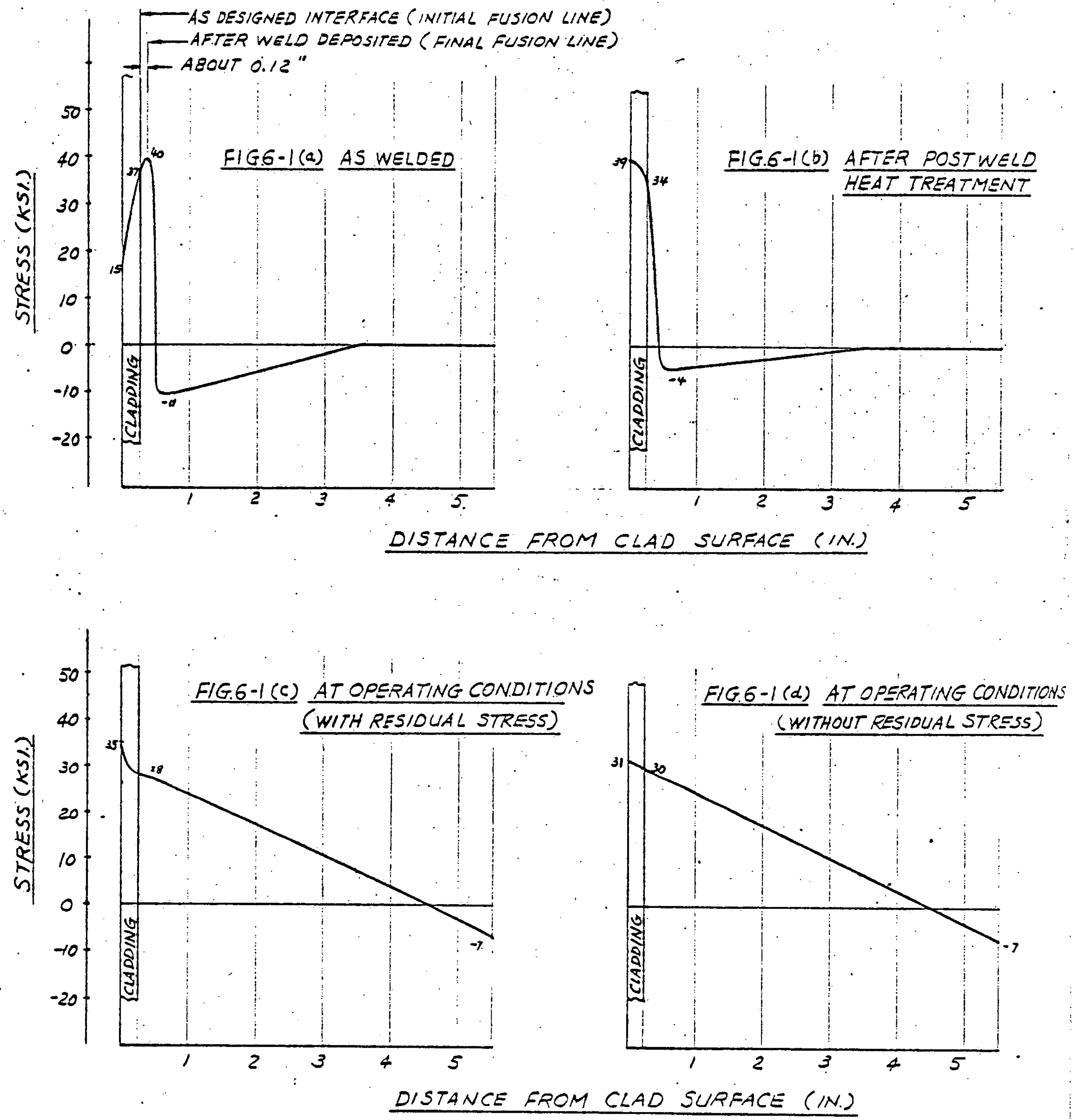
Paragraph N-414.4 and Figure N-414 of the applicable ASME Boiler and Pressure Vessel Code Section III, states that the allowable value of the intensity at any point across the thickness of a section for the sum of general or local primary membrane stresses plus primary bending stresses plus secondary stresses is 3 Sm. Sm for SA 216-WCC at 650F is 19.4 Ksi, and at 100F is 23.3 Ksi.

The pressure stresses occurring in the biological shielding ledge area of channel head wall (approximately 3.5" below the tubesheet), are examined below as a generally representative condition.

In the course of weld-cladding the channel head, plastic deformation occurs and tensile residual stresses build up during cooling to room temperature from the weld-cladding temperature. Such residual stresses are of yield-strength magnitude. The thin (1/4") cladding with a high coefficient of thermal expansion (8.2×10^{-6} in/in at 70F) is prevented from shrinking freely by the thicker (5 1/4") base metal which has a lower coefficient of thermal expansion (6.1×10^{-6} in/in at 70F). High tensile residual stress develops in the cladding. The peak tensile residual stress appears in, or slightly below, the final fusion interface between the two metals, and is of the order of the yield strength of the base metal. The major portion through the thickness of the base metal is in compression, to counterbalance the tensile stress in the cladding. However, this compressive stress in the base metal is at a much lower level, due to the very high thickness ratio between the base metal and the cladding. In fact, the effect of differential thermal-shrinkage on the base metal disappears at a depth approximately 3.5" inside the thickness of the channel wall. This stress pattern is shown in Fig. 6-1(a).

Postweld heat treatment does not erase the residual stresses in the clad region, as shown in Fig. 6-1 (b). This is again due to the large difference in thermal-expansion coefficients between the austenitic stainless steel cladding and the ferritic base metal. The differential shrinkage at room temperature (resulting from cooling down from the stress relief heat treatment temperature of 1100F) between these two metals is large enough to drive the entire cladding region to very high tensile stress. The major portion of the base metal remains in insignificantly low compressive stress.

FIG. 6-1 PREDICTED STRESS DISTRIBUTION IN THE CLADDED CHANNEL WALL



At operating temperature, a significant portion of the residual stress resulting from postweld heat treatment is relieved due to the now favorable difference in thermal-expansion between the two metals. The stress distribution shown in Fig. 6-1 (c) is for the channel weld region approximately 3.5" below the tubesheet. Service pressure stresses result in very high discontinuity pressure bending stress due to the interaction between the very thick tubesheet and the thinner channel wall. These stresses are maximum in the axial direction. The maximum residual stresses occur in the hoop direction along the direction of the cladding deposition. For conservatism, these two stresses are combined to obtain the curve in Fig. 6-1 (c). This can be compared to the calculated stress distribution neglecting the residual stresses due to the cladding, as shown in Fig. 6-1 (d).

It is apparent that during service, the residual stresses and difference in thermal expansion serve to reduce the peak pressure stress at the surface of the base metal. This reduces the probability of propagation of discontinuities into the base metal.

6.2 Corrosion

Corrosion data for the analysis of the integrity of the Indian Point Unit No. 3 channel head can be taken from the results of Westinghouse tests.

In a primary loop test in which reactor coolant conditions were simulated, the data shown in Table 6-1 were developed for SA 556-C2 carbon steel, a wrought steel chemically similar to SA 216-WCC, showing a corrosion rate of 0.5 mils/year for unclad carbon steel exposed to PWR conditions during a typical fuel cycle. On this basis, in 40 years of service life, the total corrosion penetration would be of the order of 0.020".

During the 1965 refueling of the Yankee Rowe reactor, it was found that two small areas (approximately two inches square) of the lower head cladding had been worn away by specimens and debris when a material irradiation capsule broke loose during service. Corrosion tests were initiated to determine whether or not operational or reactor vessel safety problems could result (Footnote 10). As shown in Table 6-2 the materials involved at Yankee Rowe and the materials used in the tests are chemically similar to the materials of concern in the Indian Point Unit No. 3 steam generator channel heads. Therefore, the test data is reasonably applicable to the condition in the Indian Point Unit No. 3 channel heads.

Specimens of A302B were exposed to boric acid solution containing 2500 ppm boron, both aerated and deaerated, at temperature

10) "Absorption of Corrosion Hydrogen by A302B Steel at 70F to 500F" WCAP-7099, December 1, 1967

Table 6-1

A. Environment #1	Start Up	Operating	Hot Shutdown	Shutdown
Temperature °F	100 to 630	630	630	180
Velocity, fps	14	14	14	14
Chemistry:				
Boron (as H_3BO_3) ppm	0	1200-0	2000	2000
Lithium (as LiOH), ppm	1 to 2	0.5 to 2	1 to 2	1.5 to 2
Chloride, ppm	1.0 to 0.15	< 0.15	< 0.15	< 0.15
Fluoride, ppm	< 0.15	< 0.15	< 0.15	< 0.15
Oxygen, ppm	7 to 0.1	< 0.1	< 0.1	2.0
Hydrazine, ppm	21 to 0.1	0.1	-	-
Hydrogen, cc/kg	0 to 30	30	30 to 0	0
Exposure Time, days	15	365	28	21
Material	SA-556-C2 Carbon Steel			
Corrosion Rate	105 mg/dm^2/429 days (0.6 mils/429 day or approx. 0.5 mils/year)			

varying from room temperature to 500F. The corrosion of the A302B steel, and the resultant hydrogen pickup in the steel was determined. The test program included exposure of isolated coupons of the A302B steel as well as coupons coupled to 304 stainless steel.

The results indicated the corrosion rate of A302B in air saturated boric acid (2500 ppm boron) was the maximum at 140F at 2450 mg/dm^2mo which is equivalent to 1.4 mils/mo. As the isolated A302B coupons and the A302B coupons coupled to 304 stainless steel exhibited the same corrosion rates for all temperatures tested, it was concluded that neither galvanic nor crevice corrosion was a major factor. The corrosion rates appeared to have attained a steady state value after about three weeks exposure. The results also indicated that in deaerated solutions of boric acid (2500 ppm boron), corrosion of A302B at 70F was 28 mg/dm^2mo, (equivalent to 0.016 mils/mo). Because of the short duration of high temperature tests, approximate extrapolations were made indicating that at 500F, the corrosion penetration would be 0.24 mils per year.

On the basis of these test results, and on the assumption that the unit will be in service 80% of the time, with half of the shutdown period at hot stand-by, the weighted corrosion rate would be less than 2 mils per year and the total corrosion penetration anticipated in 40 years of service life would be of the order of 0.075". It is anticipated that any corrosion of the base metal will be in the form of a pitting attack, as seen in the Japanese

JPDR boiling-water reactor vessel (Footnote 11).

Measurements of bare carbon steel surfaces exposed to actual service in PWR environments have demonstrated that predictions based on the test data are extremely conservative. The clad void area in the Yankee Rowe reactor has been measured by replication using underwater impression techniques during refueling shutdowns. No changes in depth of penetration have been measured to date after years of service.

It is conservatively calculated that the critical flaw size for the SA 216-WCC channel head in the area of highest service stresses is no less than 2 inches in depth with a flaw taken as a discontinuity with a sharp leading edge. As the most conservatively postulated corrosion of 0.075" is considerably less than one-tenth the critical flaw, and as it is reasonable to expect that the corrosion penetration into the base metal will be in the form of rounded pitting rather than a sharp discontinuity, it is concluded that the postulated corrosion penetration will not affect the integrity of the channel head.

The Westinghouse report, (Footnote 10, Page 6-6), also determined the hydrogen pickup as a result of the corrosion of the isolated A302B samples and the A302B samples coupled with stainless steel.

11) T. Kondo, H. Nakajima and R. Nagasaki, "Metallographic Investigation of the Cladding Failure in the Pressure Vessel of a BWR," Nuclear Engineering and Design, Vol. 16, No. 3 (1971) pp. 205-222

Table 6-2

Comparison of Westinghouse Test Materials with Indian Point No. 3 Materials

	Carbon Steel		Cladding	
	Test Material	IP No. 3 S.G. Channel Head	Test Material	IP No. 3 S.G. Channel Head
Carbon	0.20	0.19 - 0.25	0.08 max	0.10
Manganese	1.34	1.18 - 1.23	2.0 max	1.27
Sulfur	0.02	0.004 - 0.013	0.03 max	0.12
Phosphorus	0.12	0.010 - 0.012	0.045 max	---
Silicon	0.20	0.41 - 0.50	1.0 max	0.50
Molybdenum	0.47	0.02 - 0.03	----	---
Nickel	--	0.09 - 0.36	8.0 - 12.0	7.3 - 7.7
Chromium	--	0.10 - 0.17	18.0 - 20.0	16.5 - 19.3

It was determined that the maximum hydrogen pickup in the A302B steel was less than 2 ppm for corrosion in aerated solutions and less than 1.5 ppm for corrosion in degassed solutions. The hydrogen pickup at elevated temperatures was less than that at low temperatures. Furthermore, no increase in hydrogen pickup with time could be determined for any test condition. Therefore, it can be concluded that no significant hydrogen buildup from corrosion will occur at either high or low temperatures in aerated or deaerated solutions, and that hydrogen embrittlement of the channel heads will not occur.

6.3 Service Experience

Service experience with cladding which has similar imperfections has shown no adverse effect on performance. Over the past 20 years, there have been many instances where imperfections appeared in the corrosion resistant cladding of several nuclear steam supply system vessels. The imperfections have been attributed to corrosion, hot cracking, improper welding, metallurgical conditions, or various combinations of these. Extensive metallurgical and structural investigations were made for each incident. In all cases, the imperfections were confined to the corrosion resistant cladding, and in no case did the imperfections extend into the underlying base metal.

In the Yankee-Rowe pressurizer, the vessel containing cracked cladding has seen service for more than ten years. Periodic inspections at refueling intervals have confirmed that crack growth has not taken place. Furthermore, this plant has operated successfully even though low alloy steel has been exposed to the primary coolant. Reports of the Yankee-Rowe examinations and service have been provided periodically to the AEC (NRC).

In the head of the JPDR reactor vessel (Footnote 11, Page 6-8), cracking in the weld deposited cladding was reported to be interdendritic near the surface and transdendritic further inward. Base material, A302B, was exposed in the course of removing the cracks. Unrepaired areas were deliberately left for future observation. In 1968, after approximately two years operation with condition noted, a detailed metallographic examination revealed only minor pitting about 0.004" deep in the exposed base metal at the tip of some of the cracks. The environment was fairly aggressive since 35 ppm oxygen was present in the steam phase. (Footnote 12) The depth of pitting is less than would be anticipated on the basis of the Westinghouse corrosion test data.

This service experience indicates that the imperfections in the cladding are not unduly detrimental, and lends credibility to the prediction of vessel integrity.

12) Letter Report JP-M-1, Tatsuo Kondo, Japan Atomic Energy Research Institute, April 10, 1968

SECTION 7 - EVALUATION OF ALTERNATIVE ACTIONS

7.1 Alternatives Considered

The alternatives available for further action are as follows:

1. Accept the present condition of the cladding.
2. Top clad the existing cladding with a ductile stainless steel deposit.
3. Remove all indications and do no further work on the cladding.
4. Remove all indications and restore the cladding to its original thickness.
5. Remove the cladding completely and reclad all the heads.
    - a) In place
    - b) By severing and removing the head
        - 1) With recladding at Indian Point
        - 2) With recladding at Tampa

Each of these alternatives is discussed below.

7.2 Accept the Present Cladding Condition

It has been shown in Sub-section 5.3, that future in-service extension of the imperfections in the cladding will not be significant, and that propagation of discontinuities into the base metal is not at all probable. Furthermore, it has been shown that no significantly deleterious effects will result from either the present condition of the cladding or the condition that is anticipated at the end of service life of the steam generator. Therefore, from a technical point of view, acceptance of the present cladding condition is justified.

Acceptance of the present cladding condition is also justified by reference to the applicable sections of the ASME Boiler and Pressure Vessel Code, as explained in sub-section 4.5.

7.3 Top Clad Existing Cladding

It has been suggested that the present surface cladding be overlay clad with additional filler metal without elimination of the surface imperfections. This is technically feasible, and it would produce a final surface free of imperfections but some portion of the original cladding imperfections would remain beneath the re-melted cladding and the new cladding deposit.

This method of producing a liquid penetrant indication-free surface is not recommended, as it entails a major, time consuming welding program and does not eliminate cladding imperfections completely.

7.4 Remove Indications Only

Although known imperfections at present cover less than 10% of the total surface area of the steam generator channel, recent attempts at repair have demonstrated that, in the course of removing cladding by grinding, new liquid penetrant indications develop adjacent to the ground areas, increasing the extent of the surface to be reworked. In many instances, it was necessary to remove cladding down to the base metal in order to remove the indications completely.

Consequently, it is estimated that the result of an attempt to remove all known imperfections would be to rework a considerably larger surface than is now suspect, and to expose a considerably larger area of base metal. Not only would this result in larger volumes of base metal corrosion products, but it would not preclude the possibility of new imperfections developing during service because of the stress cycles to which the cladding will be exposed during service and the known low ductility of the cladding grain boundaries.

Therefore, removal of the imperfections in the cladding without restoration of the metal removed is not recommended.

7.5 Remove Indications and Restore Cladding

During the course of the recent attempt at repair it was found that deposition of weld-cladding in weld areas with or without preheat resulted in additional liquid penetrant indications developing adjacent to the repair and somewhat removed from the repair. Also, local preheat frequently resulted in the development of additional liquid penetrant indications at the boundaries of the heated area.

Consequently, it is anticipated that attempts to remove all known imperfections and to restore the metal removed would result ultimately in complete removal of the cladding and in complete recladding of the channel heads.

Deposition of cladding on base metal would require either a full stress relief treatment at 1100F or the use of a temperbead technique for cladding deposition. A full stress relief in-place does not appear to be feasible because of the problems anticipated in insulating the sections to be heated, and in accomodating the interactions between the channel head on one hand and the primary piping and steam generator supports on the other hand.

Consequently, it would be more reasonable to use the temperbead technique. In order to minimize the preheat and post weld heat cycles required, it would be prudent to deposit the first layer of clad in one operation. Judging from the results of the initial repair attempts, this alternative would soon develop into one where the entire cladding would be removed and replaced.

This alternative is not recommended and is discussed in detail below in Sub-section 7.7.

7.6 Remove Cladding Completely

Removing the cladding completely could be accomplished in place, either by use of hand tools or a machine tool.

Hand tools that could be considered are the conventional hand held grinders and rotary burrs. The objection to hand work is the large time and manpower requirement, and the possibility of inadvertent damage to the channel heads, tubes or tube-sheets.

There are available machine tools that are capable of machining the stainless steel cladding from a base of carbon steel. This has in fact been accomplished as a trial on a piece of plate formed to simulate the surface of a 5' radius cylinder. However, the trial work was accomplished down-hand and the controls were largely assisted by the weight of the machine tool on support rollers. Additional work would be necessary to design a mounting and control arrangement so that the tool could remove the cladding up to the Inconel/Stainless Steel interface without cutting into the steam generator channel head.

If the cladding was not restored, the corrosion conditions would be somewhat similar to those which exist in steam drums in conventional fossil plants. It is not anticipated that the PWR environment, either during service or during outages, would be deleterious to the steam generator channel head. However, large volumes of carbon steel corrosion product could be generated during service which may overload the systems designed to keep the coolant clean.

Consequently this is not considered to be an acceptable alternative.

7.7 Remove Cladding Completely and Reclad

Removing the cladding completely and recladding was mentioned in sub-section 7.5. It is conceivable that this could be accomplished in several ways. The simplest of these is a machining and recladding in place.

Table 7-1 is a list of the major operations that would be required. It has been estimated that this work could take a year or more to accomplish at a direct cost of approximately one million dollars and an indirect cost approaching one hundred million dollars, considering the delay in plant start-up. On satisfactory completion of the work, the cladding would probably be in a fully acceptable condition. A variation of this alternative is the partial removal of the cladding to reduce the thickness of clad to approximately 1/8" and then to re-fuse the remaining cladding. If this procedure could be controlled accurately enough, it could reduce the amount of cladding to be machined and could eliminate the need to use the temperbead technique and the associated need for preheat and post-weld heat. This would probably reduce the time required for completion.

For either procedure, it is necessary to consider the fact that this has never been attempted as an on-site operation, and successful completion requires precision machining and welding in the confines of a steam generator channel head.

TABLE 7-1

Operations Required for Steam Generator Channel Head Recladding in Place

1. Design of machine tool
    a) Fabricate mock-up
    b) Procure material
2. Fabricate machine tool and accomplish preliminary work in head
3. Machine remove cladding
4. Hand finish
5. Examine by liquid penetrant
6. Preheat
7. Clad first layer using machine tool plus automatic GTAW head
8. Machine remove half of deposit (as required in temperbead technique)
9. Examine by liquid penetrant
10. Clad second layer
11. Post-weld heat
12. Examine by liquid penetrant

As noted above, a major concern about the probability of success of the cladding removal and restoration is the fact that operations would be confined in the steam generator channel head. The obvious alternative to avoid such confined operations is to sever the head from the shell and separate the two for easy access to the head. Further alternatives are 1) keep the head in place and raise the shell, or 2) support the shell in place and remove the head. If the head were to be removed, second order alternatives to consider would be 1) remove the head to a suitable location within the Indian Point Unit No. 3 containment, or 2) remove the head to Tampa for rework in the Westinghouse shop.

Of these alternatives, the procedure of severing the head and raising the shell appears to be the most practicable. Table 7-2 is a list of the major operations that would be required. It has been estimated that this work would require more than 2 years to complete. Although the work on the head itself would be facilitated, as compared to working inside the water boxes, severe disadvantages of this procedure are the need to design and erect an alternative support for the steam generators and to reweld the head to the shell in place and on-site.

TABLE 7-2

Operations Required to Sever Steam Generator Channel Head & Reclad in Place

1. Support Steam Generator
2. a) Machine cut feedwater & steam line
   b) Remove lateral restraints
   c) Arc cut divider plate/tube sheet
3. Install cutting track
4. Plasma-arc cut head/shell
5. Raise steam generator
6. Remove existing cladding
7. Examine by liquid penetrant
8. Preheat head to 350F
9. Deposit first layer of clad
10. Remove half of deposit (as required by temperbead technique)
11. Deposit second layer of clad
12. Post weld heat to 450F
13. Examine by liquid penetrant
14. Prepare head for rewelding
15. Prepare shell for rewelding
16. Relocate steam generator
17. Preheat head to 350F
18. Plasma arc weld shell/head
19. Examine by radiography
20. Continue weld
21. Examine by radiography
22. Continue weld
23. Examine by radiography
24. Post weld heat treat
25. a) Examine by ultra-sonics
    b) Reweld divider plate/tube sheet
    c) Reweld feedwater & steam lines
    d) Install lateral restraints
26. a) Remove track
    b) Remove supports

It is conceivable that the steam generator shell could be supported and raised utilizing the polar crane. It would be necessary to fabricate a cradle which would be fitted to the conical section of the shell, and a lifting rig from the cradle to the crane. Additional supporting structure would be required for the crane itself. All restraints, including the seismic restraints, and feedwater and steam lines would have to be severed and subsequently restored.

The weld between the steam generator channel head and the shell is a full penetration joint 5 1/4" thick, and is required to pass radiographic inspection. During fabrication, this joint is made by submerged arc, with the steam generator on rollers and its axis horizontal. On site, the steam generator axis is vertical, and in a fixed position. Whether the joint is completed by manual welding, or by a to-be-designed automatic rig, it is improbable that the weld as initially deposited would meet radiographic inspection acceptance standards per Section III. It would be necessary to interrupt the welding frequently for in-process radiographic examination and repair, during all of which the preheat temperature would have to be maintained. After welding is completed, a full stress relief at 1100F would be required. The difficulties in accomplishing an on-site stress relief are discussed above in sub-section 7.5. The probability of successfully completing three weld joints of this size is considered to be low.

This alternative includes the second order alternatives of removing the head and recladding it either at a lay-down location at Indian Point or at the Westinghouse shop at Tampa. While such removal would further facilitate head cladding removal and replacement, as compared to accomplishing this work in-place, additional difficulties are added to those discussed above. For example, in order to remove the head from its present location (after it is parted from the shell), severing the primary coolant lines and extensive modification of the steam generator support structure would be necessary.

For these reasons this alternative is not recommended.

SECTION 8 - EVALUATION OF SURVEILLANCE TECHNIQUES

8.0 It is demonstrated in Section 6.0 that the existing imperfections do not compromise the integrity of the channel head and will not adversely affect operation of the unit. It is also predicted that the imperfections will not develop into unacceptable defects. A surveillance program would be of value to provide assurance that the predictions remain valid during the service life of the steam generators.

8.1 Definition of Allowable Flaw Size

As a first step in evaluating and selecting a surveillance technique it is necessary to determine the size of imperfection considered to be unacceptable.

It has previously been stated that the imperfections now present in the cladding may extend to, but not into, the base metal. Sub-section 5.3.1 predicts that such imperfections may propagate in the cladding or new ones may develop in the cladding. These imperfections are shown to be within the range of acceptability in Section 6.0 of this report.

Sub-Section 5.3.2 predicts that the cladding imperfections will not propagate into the base metal. It is considered possible that corrosion of the base metal at the root of a cladding imperfection reaching the base metal could extend an additional 0.075" during the service life of the steam generator. Therefore, the surveillance program selected should be capable of reliably identifying a discontinuity which is equal to the cladding thickness (normal 0.3") plus the corrosion predicted (0.075"), and measuring any unexpected growth from 0.375" to the maximum flaw allowable by code for continued operation.

8.2 Non-destructive Examination Alternatives Considered

Non-destructive examination techniques considered for use as a surveillance tool are as follows:

1. Eddy current examination
2. Magnetic flux leakage
3. Ultrasonic examination
4. Conductimetric examination

A reference standard for examination from the clad-side was prepared using clad samples available at Westinghouse, with notches cut with a grinding wheel and by electrochemical machining to simulate the flaw indications in the steam generator channel head. A reference standard for examination from the outside surface was prepared using an actual channel head available at Tampa, also with notches of various depths cut and electro-chemically machined in the cladding to simulate the flaw indications present in the steam generator channel head.

8.3 Eddy Current Examination

A gap probe as well as a small pancake probe were used with the Zetec-Automation EM3300 instrument. With this combination the notches could be detected and the shallow notch could be differentiated from the medium and deep notches but the latter two could not be distinguished. When the tapered notch was used to calibrate the test, it was found that the calibration curve was not monotonic and two depth values were related to each instrument reading.

A Halec eddy current instrument was also calibrated on a tapered notch. Here again the calibration curve was not single-valued, nevertheless, the unit was selected for trial use in examining the Indian Point Unit No. 3 steam generator channel head cladding.

8.4 Magnetic Flux Leakage

The magnetic background of the clad specimens was extremely variable and with the resultant high noise level the electro-chemically machined notches could not be detected.

8.5 Ultrasonic Examination

a) Cladding-side examination:

On the reference block with little or no cladding, detection and depth estimation of the electro-chemically machined notches was possible. On the two clad specimens containing electro-chemically machined notches detection was questionable and depth determination was not effective.

b) Outside surface examination

Detection and depth estimations of ground and electro-chemically machined notches were possible. Moreover, areas could be examined relatively rapidly. This technique was selected for additional development and trial use in examining the Indian Point Unit No. 3 channel head cladding.

8.6 Conductimetric Examination

The Uresco CC-400, AC conductimetric test instrument used with the 4-electrode probe was calibrated on the notched standard. The calibration curve was single valued. Although the instrument was ineffective on short electro-chemically machined notches, it proved quite effective on slots, cracks, and notches whose length was greater than twice their depth. This unit was also selected for trial use in examining the channel head cladding at Indian Point Unit No. 3.

8.7 Evaluation of NDE Alternatives

a) Cladding-side examinations:

Six indications in the steam generator channel head cladding were selected for trial. Readings were taken by two investigators. Then the indication was removed with a carbide burr and the resultant depth of cavity was measured.

The eddy current readings were grossly high, and further consideration of examination by eddy current was terminated. The conductimetric readings varied up to 125% high. In order to use the conductimetric probe, good contact with the clad surface must be insured. This would require initial preparation of the surface to remove welding irregularities before any future surveillance, and, for future examinations, a re-preparation of the surface to remove any crud or oxide deposits. Development of a new discontinuity between the probe contacts could negate all previous readings. Furthermore, the number of imperfections that could be monitored would be small because of the radiation-imposed limitation on personnel exposure in the steam generator water box.

Ultrasonic depth measurement from the outside surface, as used on a section taken from a channel head, was reasonably accurate within narrow ranges. Large areas could be monitored without excessive exposure to radiation.

In summary, no satisfactory instrumented surveillance equipment has been identified to date for cladding-side examination for measuring flaw depth; however, ultrasonic examination from the outside surface appears to be a promising technique for surveillance.

SECTION 9 - CONCLUSIONS

9.0 Conclusions

It was determined by metallurgical study and test that the imperfections in the cladding of the Indian Point Unit No. 3 steam generator channel heads were probably caused by inadequate ductility of the cladding and may have been triggered or assisted by a stress corrosion mechanism.

It was demonstrated that the imperfections in the cladding are confined to the cladding and are considered within the range of acceptability of the ASME B&PV Code. It is further recognized, however, that the condition of the cladding of the Indian Point Unit No. 3 steam generator channel heads is one that would not be expected of good manufacturing practice and that it results in a requirement to extensively monitor, possibly with instrumentation, an area that normally would receive only visual examination.

It was demonstrated that the presence of cladding discontinuities does not impair the structural adequacy of the steam generator channel heads and will not have any appreciable effect on operations. It was also demonstrated that credible postulated growth of the discontinuities into the base metal, whether by corrosion or by fatigue or a combination of the two, similarly would have no deleterious effect.

Alternative methods of repair were considered, and it was concluded that repair was not required.

Alternative techniques for non-destructive examination were evaluated, and it was concluded that the development of a procedure for ultransonic examination of the interior clad surface from the outside of the steam generator channel heads is promising, but that a specific procedure would have to be developed for reliable use as a surveillance tool for measuring the depth of the imperfections in the cladding of the Indian Point Unit No. 3 channel heads. No electronic system is now known to have sufficient linear discrimination to allow direct interpretation of expected changes in the condition of the cladding.

SECTION 10 - PROPOSED ACTION

The present condition of the cladding of the channel heads of the steam generators at Indian Point Unit. 3 is considered acceptable. A surveillance program is proposed as follows:

1. Increase the Section XI requirement for visual examination of 36 square inches to a general 100% visual examination of the interior water box surface per inspection interval. In practice such visual examination could be accomplished remotely by use of a TV camera, thereby minimizing exposure of personnel to radiation, and making it possible to "zoom-in" on questionable areas for closer examination.
2. If a procedure for ultrasonic examination of the clad surface from the outside surface of the channel head can be developed to a point where its reliably indicates depths of imperfections, it would be used for surveillance of the steam generator channel heads. The objective of the ultrasonic surveillance would be to detect significant extension into the base metal of the imperfections now present in the cladding. Areas in the relatively high stress region near the biological shielding ledge have been selected so that a statistically significant number of imperfections would be included in possible future ultrasonic surveillance.

A report on the ultrasonic inspection program will be presented as a supplement to this report, identified as Appendix D.

TECHNICAL REPORT ON STEAM GENERATOR CHANNEL HEAD CLADDING

INDIAN POINT UNIT NO. 3

APPENDIX B

Summary Report on Indian Point Unit No. 3
Steam Generator Problem

By

Dr. Warren F. Savage

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Appendix B

SUMMARY REPORT ON INDIAN POINT 3 STEAM GENERATOR PROBLEM

INTRODUCTION

On July 7, 1975, I visited the Indian Point No. 3 site to inspect the defective steam generator cladding. On July 9, 1975, I visited the Westinghouse Plant at Tampa where I was able to review the preliminary draft of the Westinghouse report, inspect the cladding equipment and briefly examine two boat samples removed from the steam generators at Indian Point No. 3. On July 14, Paul McTigue visited me in Troy, and we reviewed the final draft of the Westinghouse Report. On July 16, I visited the Westinghouse Research Laboratory in Monroeville and was able to discuss the problem with Westinghouse personnel and examine six boat samples at some length. On July 18, I reviewed my observations for interested personnel from Consolidated Edison and two representatives from PASNY at 4 Irving Place. On July 23, I attended the review meeting and again presented my observations and conclusions. The following sections summarize these observations and conclusions for the record.

THE PROBLEM

The original flaws proved, upon excavation, to be cracks in the vicinity of the bead overlap and were detected in all four vessels. Many of these cracks extended completely through the cladding to the base metal interface. All cracks were predominantly intergranular, were located in the heat-affected zone produced by the overlapping weld deposit and ran parallel to the welding direction of No. 31, No. 32, and No. 34 Steam Generators. Additional penetrant indications were formed near fillet welds between the divider plate and the clad surface at the bottom of the water box.

Three types of cracks have been observed and documented in the cladding of No. 31, No. 32, and No. 34 steam generators.

1. Longitudinal Interbead Cracking. The original defects were of this form and were located in the upper portion of the heads near the biological shield. The cracks propagated along grain boundaries in the heat-affected zone caused by bead overlap. Cracking was usually but not exclusively near the fusion boundary, where the microstructure exhibited little or no ferrite and often extended throughout the entire thickness of the cladding.

2. Transverse Cracks Adjacent to Repair Welds. Almost without exception the deposition of repair weld beads or re-fusing of the existing cladding with GTA caused grain boundary cracks to propagate into the original cladding in a direction normal to the welding direction. This type of cracking occurred wherever repairs were attempted regardless of location. In no case however were PT indications observed in either repair welds, stringer beads, refused areas.

3. Craze Cracking. This form of cracking was located predominantly in the lower half of the heads and was discovered as far as 30-in. from any repair weld. However, so far as could be ascertained, this cracking was confined to regions subjected to the 350-400 preheat and post weld heat treatments. (None was identified in steam generator No. 33 where repair welding was performed without preheat).

CRACK MORPHOLOGY

In all cases, the cracking was intergranular and in most cases interdendritic. It is important to note that the grain boundaries in the cladding, although predominantly coincident with the interdendritic boundaries produced during solidification, may migrate and become transdendritic over small distances during cooling to room temperature. In all boat samples that I examined, there was evidence of grain boundary films which appeared either grey or mottled grey & black in the as-polished condition. The thickness of this film was in most cases less than 1 micron and so could not be identified by electron beam microprobe analysis.

Auger electron spectroscopy of the surface of a crack in one boat sample showed evidence of the presence of carbon in the form of carbides (presumably chromium carbides), sulfur and a surprisingly high level of oxygen. No evidence of magnesium, sodium, potassium (which are present in sea water) or calcium was found although a trace of chlorine was present. The level of silicon was estimated to be no greater than nominal, thus ruling out the possibility of a silicate network along the grain boundaries as the embrittling agent.

Although Westinghouse representatives hypothesize the cracking to be stress corrosion cracking, the morphology is not that of stress corrosion cracking. Stress corrosion cracking is predominantly transgranular in nature whereas all cracking I observed was almost exclusively intergranular.

Furthermore, the vessels all received a stress relief treatment subsequent to the last known exposure to sea water. During heating from room temperature to 1100°F, the stainless steel, if unrestrained, would expand about 2.5 x 10^{-3} in/in., more than the carbon steel in the bowl. However, the stainless steel cladding is almost totally restrained in the plane of the surface by the thick wall of the head. Thus, even if yield strength residual tensile stresses were present, the austenitic stainless steel would experience a bilateral compressive strain of approximately 1.5 x 10^{-3} in./in. Upon cooling to room temperature the stainless steel would then experience a bilateral shrinkage strain about 2.5 x 10^{-3} in./in. greater than that in the plain carbon steel. These bilateral tensile strains should have been more than adequate to open any stress-corrosion cracks which were too tight to be detectable prior to the stress relief. Since PT inspections were carried out after the final stress relief it is therefore difficult to believe that all stress corrosion cracks could have escaped detection at that time.

Furthermore, the craze cracking is predominantly observed in the lower half of the bowl which would have received minimum exposure to the ingested sea water.

DILUTION OF CLADDING

The average composition of two boat samples removed from steam generator No. 34 is given in the Westinghouse report as:

C - 0.103%, Ni - 7.72%, Cr - 17.1%

Unfortunately, the analyses of SG34 is not available at this time, but based upon the analyses of SG Nos. 31, 32, and 33, it is unlikely that the chromium is greater than 0.2 or that the nickel is greater than 0.5%, and the maximum allowable carbon is 0.25%. These values have therefore been used as conservative estimates of the composition of the carbon steel casting.

In a telephone communication on July 21, 1975, L.K. Poole provided the following analysis for the filler wire used in cladding SG No. 31, 32, 34:

C - 0.019, Ni - 13.81, Cr - 24.88

From the above data one can calculate the % dilution as follows:

let x = volume fraction of base metal in weld.

1-x = volume fraction filler metal.

100 x = dilution

B = % of element in base metal

F = % of element in filler metal

W = % of element in weld metal

then xB + (1-x) F = W   Equation 1

From the preceding equation the dilution factors were calculated as follows:

	C	Ni	Cr
B = % in Base Metal (Assumed)	0.25	0.5	0.2
F = % in Filler Metal	0.019	13.81	24.88
W = % in Weld Metal	0.103	7.72	17.1
% DILUTION	36.3	44	31.5

Since Westinghouse specifies a maximum of 30% dilution it appears that this cladding experienced excessive dilution with base metal. Since the casting could contain harmful impurities such as arsenic, and antimony, excessive dilution of cladding with base metal may explain the difficulty in repair welding this cladding.

The composition of the cladding on steam generator No. 34 was used to locate the alloy on the Delong constitutional diagram. The chromium and nickel equivalents for this composition are 17.83 and 11.46, respectively. This places the alloy in the austenite + ferrite + martensite region and predicts a ferrite number of between 3 and 4. However, the slow cooling rate in the heat-affected zone preduced by the overlapping beads renders the microstructure in these regions almost completely devoid of ferrite and thus probably more sensitive to microfissuring.

PROBABLE CRACKING MECHANISM

The original flaws were located after hot functional testing. It is possible that they were present prior to testing but escaped detection in previous dye penetrant inspection. Their location at the rough interface between overlapping weld beads would have made their detection somewhat difficult. It is also possible that a network of microfissures, often present but not detectable by PT inspection, linked up during testing to form a continuous subsurface crack which intermittantly intersected the surface.

The cracks formed during repair welding are believed to result from grain boundary embrittlement. The microstructure of the claddings shows a coarse solidification subgrain structure and numerous grain boundaries with continuous or near-continuous films of a grey or mottled grey and black constituent.

Although attempts to identify this film by Auger electron spectroscopy were inconclusive, the crack surfaces show high carbon (as carbide), oxygen, sulfur, and chromium.

SEM measurements of particles on the fracture surface of one boat from No. 34 revealed concentrations of silicon, chromium, with considerable sulfur and manganese present. A deposit in a crack surface in this boat showed evidence of aluminum, silicon, sulfur, chlorine, potassium, calcium, chromium, iron and nickel and is one of the major arguments used to support the Westinghouse hypothesis of stress corrosion cracking. However the chlorides could as readily have been deposited in an existing crack as to have caused the cracking.

No PT indications were observed in any repair welds, stringer beads, or GTA re-fused areas. This is attributed to:

1. The fact that the solidification substructure in these areas was nearly an order of magnitude finer than in the original cladding and no grain boundary films could be detected.

2. If the embrittling agent in the original cladding was a carbide network produced during stress relief, the carbides would have been redissolved in the molten metal.

3. If the embrittling agent was an oxide or sulfide, the greater grain and subgrain boundary area in the remelted areas, repair, and stringer beads would reduce the likelihood of continuous or near-continuous films being formed.

The location and morphology of the cracks detected after repair suggests that existing microfissures on the grain boundaries served as stress concentrators and that the shrinkage strains experienced during cooling after welding and/or preheating operations caused their propagation as cracks along the embrittled grain boundaries.

The SEM photographs in Figures 30-32 of the Westinghouse report support this view. Area B (Fig. 30) has the slightly irregular and rounded appearance typical of a microfissure. The majority of the crack path in the other areas is along interdendritic grain and subgrain boundaries and is decorated by numerous small particles.

POTENTIAL FOR EXFOLIATION

Although I do not believe that the possibility exists for exfoliation of pieces of the cladding by separation at the base metal interface, there are scattered cracks near the surface which run parallel or nearly parallel to the surface.

In view of the large number of craze cracks present there exists a statistical possibility that fragments of cladding ranging from the size of a grain of sand upwards to possibly the size of a dime may exfoliate and enter the primary water system.

However the probability is low and therefore I would not anticipate more than isolated incidents of this phenomenon scattered over the entire clad surface of the bowl.

CONCLUSIONS

1. Steam generator No. 34 was clad using procedures which resulted in excessive dilution and there is no reason to believe this was not also the case in the other three generators although no analytical data was reported to me for those vessels.

2. The substructure in the weld cladding is coarse and many grain boundaries show evidence of a nearly continuous film.

3. The cracking in all instances is intergranular and appears to result from shrinkage-induced propagation of existing microfissures along embrittled grain boundaries.

4. The nature of the suspect grain boundary film has not been identified.

5. Three forms of cracking have been identified:

   1) Longitudinal Interbead Cracking
   2) Transverse Cracks adjacent to Repair Welds
   3) Craze Cracking

6. Craze cracking is predominantly in the lower half of the head where the time of exposure to ingested sea water was least and therefore stress corrosion cracking least likely.

7. The crack morphology does not support the Westinghouse argument for stress corrosion as the crack mechanism.

8. The grain boundaries in the base metal are continnuous with those in the cladding. Therefore the tips of the cracks in the cladding which extend to the base metal are located along grain boundaries in the base metal. However, this probably will not increase the likelihood of extension into the base metal significantly.

RECOMMENDATION

The consequences of the cracking in the cladding, and the potential extension of the cracking should be evaluated. If it is determined that the integrity of the vessel could be compromised, or that an unacceptable interference with operations could result, then, it is my considered opinion that the present defective cladding should be removed and the vessel reclad by the most expeditious method possible prior to being placed in service.

July 25, 1975

Warren F. Savage, Ph.D.

TECHNICAL REPORT ON STEAM GENERATOR CHANNEL HEAD CLADDING

INDIAN POINT UNIT NO. 3

APPENDIX C

Relevant Pages from ASME B&PV Code

Section III, 1965 Edition

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N-321.3 Repair of Cladding by Welding – The materials manufacturer may repair defects or unbonded areas in cladding by welding provided the following requirements are met:

(a) Prior approval is obtained from the vessel manufacturer.

(b) The welding procedure and the welders or welding operators are qualified in accordance with N-542 and with Section IX of the Code.

(c) The defective or unbonded area is removed and the area prepared for repair is examined by a magnetic particle method in accordance with N-626 or by a liquid penetrant method in accordance with N-627.

(d) The repaired area is examined by a liquid penetrant method in accordance with N-627 and by the ultrasonic method in accordance with N-321.1.

(e) The location and extent of the weld repairs together with the repair procedure and examination results are recorded and transmitted as a part of the certification for the purposes of N-514.2.

N-322 Nondestructive Examination of Forgings and Bars – Forgings and bars shall be examined in the as-furnished condition by the ultrasonic and by a magnetic particle or a liquid penetrant method and shall meet the following requirements:

N-322.1 Ultrasonic Examination of Forgings and Bars

(a) Method – All forgings and bars for reactor vessels as defined in N-131*(a)* and all forgings 4 in. and over in nominal thickness for all other Class A vessels shall be examined by the ultrasonic method in accordance with ASTM A388-59, Recommended Practice for Ultrasonic Testing and Inspection of Heavy Steel Forgings, using the longitudinal-beam technique. Rings, flanges, and other hollow forgings shall, in addition, be examined using the shear-wave technique.

If the as-furnished condition, because of nonparallel surfaces, does not permit the ultrasonic examination of all regions, such regions shall be examined at the latest practicable stage of manufacture prior to finish machining.

(b) Reference Specimen and Acceptance Standards – The reference specimen shall have the same nominal thickness and composition as the forging. For the shear wave technique a groove 1 inch in length and 3 per cent of the nominal forging thickness in depth shall be used. The reference specimen and acceptance standard for longitudinal wave technique shall be as described in N-321.1*(b)* and *(c)*. Screen indications in excess of that produced by the standard groove defect in the shear-wave examination are unacceptable unless the defects are removed and the forging is repaired.

N-322.2 Magnetic Particle Examination – Forgings of magnetic material shall be examined on all surfaces by a magnetic particle method in accordance with the methods and acceptance standards of N-626.

N-322.3 Liquid Penetrant Examination – Forgings of nonmagnetic material shall be examined on all surfaces by a liquid penetrant method in accordance with the methods and acceptance standards of N-627.

N-322.4 Repair of Forgings by Welding – The materials manufacturer (see N-514) may repair defects in forgings by welding provided the requirements for repair specified in N-321.2 are met.

N-323 Nondestructive Examination of Castings Castings shall be examined in the as-furnished condition by radiographic, ultrasonic, magnetic particle, and liquid penetrant methods of examination as provided herein and shall meet the following requirements:

N-323.1 Radiographic Examination – All parts of castings shall be fully radiographed to the requirements of ASTM Specification E71-52, Industrial Radiographic Standards for Steel Castings, and shall meet the requirements of Class 2 of this specification.

N-323.2 Ultrasonic Examination – All parts of castings over 12 in. thick shall be examined by ultrasonic methods in accordance with the procedures of ASTM Specification E114-55T, Recommended Practice for Ultrasonic Testing. Castings with defects shown by discontinuities whose reflections exceed a height equal to 20 per cent of the normal back reflection, or which reduce the height of the back reflections by more than 30 per cent during movement of the transducer 2 inches in any direction are unacceptable unless other methods of nondestructive testing demonstrate that the indications are acceptable, or unless the defects are removed and the casting is repaired. The above limits shall be established with the use of transducers having approximately one square inch of area.

N-323.3 Magnetic Particle Examination – Castings of magnetic material shall be examined on all surfaces by a magnetic particle method, using the examination technique in ASTM Specification E109-57T, Method for Dry Powder Magnetic Particle Inspection. Castings with defects shown by Type I indications or by indications exceeding Degree I of Types II, III, IV, and V of ASTM Specification E125-56T, Reference Photographs

N-432 Detailed Analysis — A detailed stress analysis of all major structural components shall be prepared in sufficient detail to show that each of the stress limitations of N-414 is satisfied when the vessel is subjected to the loadings of N-447. As an aid to the evaluation of these stresses, formulas and methods for the solution of certain recurring problems have been placed in Appendix I, as follows:

Article	Item
I-1	Tentative Thickness of Shells and Heads
I-2	Analysis of Cylindrical Shells
I-3	Pressure Stresses in Spherical Shells*
I-4	Pressure Stresses in Ellipsoidal Heads*
I-5	Pressure Stresses in Flat Heads*
I-6	Pressure Stresses in Openings for Fatigue Evaluation
I-7	Discontinuity Stresses*
I-8	Thermal Stresses*
I-9	Stresses in Ligaments*
I-10	Experimental Stress Analysis
I-11	Stresses Due to External Pressure
I-12	Stresses in Bolting

*In course of preparation.

N-440 GENERAL DESIGN RULES

N-441 Design Pressure — The specified design pressure[1] shall not be less than the maximum difference in pressure between the inside and outside of the vessel, or between any two chambers of a combination unit, which exists under the specified operating conditions. It shall be used in the computations made to show compliance with the stress intensity limits of N-414.1, N-414.2, N-414.3, N-416, N-417.1, N-417.2, N-417.6, and N-417.7. The actual operating pressure at the appropriate time shall be used in the computations made to show compliance with the stress intensity limits of N-414.4, N-414.5, N-415, N-416.1, N-416.2, N-417.3, N-417.4, and N-417.5. Vessels shall be designed for at least the most severe condition of coincident pressure and temperature which exists under the specified operating conditions.

N-442 Design Temperature — The specified design temperature shall be the actual maximum metal temperature which exists under the specified operating conditions for each area of the vessel considered. It shall be used in computations involving the design pressure and coincidental mechanical loads. The actual metal temperature at the point in question shall be used in evaluating peak stresses and in other computations where the use of the actual operating pressure is allowed.

N-443 Corrosion — Vessels or parts thereof subject to thinning by corrosion, erosion, mechanical abrasion, or other environmental effects shall have provision made for these effects during the design or specified life of the vessel by a suitable increase in or addition to the thickness of the base metal over that determined by the design formulas. Material added or included for these purposes need not be of the same thickness for all parts of the vessel if different rates of attack are expected for the various parts.

N-444 Cladding — The following rules apply to the analysis of clad vessels constructed of material permitted under this Subsection (see Table N-421).

(a) No structural strength shall be attributed to the cladding, except where bearing stress is involved.

(b) The following dimensions shall be used in the design of the vessel:

(1) For vessels subjected to internal pressure, the inside diameter shall be taken at the nominal inner face of the cladding.

(2) For vessels subjected to external pressure, the outside diameter shall be taken at the outer face of the base metal.

(c) When the nominal thickness of the cladding is 10 per cent or less of the total nominal thickness of the component, the presence of the cladding may be completely neglected in the stress evaluation except as required in *(a)* and *(b)*.

(d) In performing a fatigue analysis in accordance with N-415.2, the presence of the cladding shall be considered with respect to both the thermal analysis and the stress analysis, and the stresses in both materials shall be limited in accordance with the design fatigue curve. However, when the nominal thickness of the cladding is ten per cent or less of the total nominal thickness of the component, the presence of the cladding may be neglected in accordance with *(c)* or may be considered, at the option of the designer.

N-445 Welds Between Dissimilar Metals[2] — Unless calculations show that the stress limits of

[1] It is recommended that the specified design pressure provide a suitable margin above the pressure at which the vessel will be normally operated to allow for probable pressure surges up to the setting of the pressure-relieving devices.

[2] Caution should be exercised in design and construction involving dissimilar metals having different coefficients of thermal expansion in order to avoid difficulties in service under extreme temperature conditions or with unusual restraint of parts such as may occur at points of stress concentration.