WNET - 116

RELIABILITY OF VARIOUS TUBE-TO-TUBESHEET WELD CONFIGURATIONS

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ABSTRACT

Through the application of FMEA and FTA Techniques the reliabilities of various tube-to-tubesheet weld configurations consisting of different combinations single or duplex tubes and single or double tubesheets with or without leak detection are investigated for application to LMFBR steam generator design. Based on substantial failure experience accumulated on PWR units, the study confirms the high reliability these welds possess and in particular identifies the tube-to-boss fillet weld as the most efficient, reliable design.

I. INTRODUCTION

The subject of tube-to-tubesheet joints has received a considerable amount of attention by welding engineers during the past few years. It is generally accepted that as most welding processes, the efficiency of the joint is dependent on metallurgical, electrical and mechanical considerations. By adequate study of solubility rules under fast cooling conditions, solidification mechanics, surface tension rules, thermal conductivity and the electrical and thermal characteristics of the arc, reliable tube-to-tubesheet joints can be produced. However, in selecting an appropriate joint configuration it is necessary that environmental conditions such as temperature, pressure, and corrosiveness of the fluids combined with the consequence of leakage be taken into consideration. For instance, for those cases involving compatible fluids operating at relatively low pressure and temperatures, a simple expansion roll or non-metallic joint might be acceptable. Conversely, for some applications such as LMFBR heat exchangers, where a leak could result in a significant explosion it is imperative that the tube-to-tubesheet joints be of the highest reliability. This reliability not only reflects the resulting quality of the fabrication process but it also must account for the adequacy of the non-destructive inspection of the joint. However, since it is extremely difficult to adequately inspect tube-to-tubesheet welds, the reliability of these joints must rely heavily on the ability to fabricate high quality reproducible welds.

The operating experience of heat exchanger tube-to-tubesheet joints for nuclear applications is basically constrained to PWR systems where the weld configuration is primarily a fillet or a recessed type joint. Some of these joints have been complemented by a partial or full depth roll of the tube to primarily avoid stress corrosion cracking of the heat exchanger tubes in the crevice region. Up to now these weld joints have exhibited an extraordinary amount of reliability. Similar experience with LMFBR tube-to-tubesheet joints is very limited. However, this limited data tends to confirm the fact that as in the case of PWR units, the LMFBR steam generator fabricator undergoes a learning process (an observed reduction in the number of necessary in house weld repairs from time T_1, fabrication initiation, to time T_2) which ultimately results in very reliable weld joints. For instance, early experience with sodium steam generators indicated some problems with tube-to-tubesheet weldments. Experience with the Fermi steam generators [1] indicates that after four or five years of operation out of which only a small portion was at rated conditions (885 psi, 820°F), 430 2¼Cr-1Mo tube-to-tubesheet welds were found to be leaking. These weld failures were primarily attributed to poor joint designs, high inclusion counts in tube-sheet and tubes, inconsistent welding practices (for instance, failure to pre- or post weld heat treat and lack of sufficient cleanliness). More recent experience with 2¼Cr-1Mo weldments indicate a substantial improvement in the reliability of the joint. For instance, out of 1020 water side tube-to-tubesheet joints in the EBR-II units operating at 1500 psi, 800°F for 11 years only one weld was found to be leaking [2].

The availability of an LMFBR steam generator as well as its reliability against a sodium-water reaction depends to a large extent on the reliability of tube-to-tubesheet welds against leaks and the number of weld joints involved in the design. At the same time, the availability and reliability of the unit is also very strongly dependent on the failure rate of heat exchanger tubes. An earlier study carried out at the WTD brought out the substantial improvement in reliability achieved by employing a duplex tube concept relative to that obtained from a single wall tube unit [4]. Since at least twice as many tube-to-tubesheet welds are required in a duplex tube heat exchanger than in an equivalent single wall unit, it is therefore necessary to assess the reliability of tube-to-tubesheet joints in order to establish the relative merits of the different LMFBR steam generator design concepts utilizing their quantitative measure of reliability against a sodium-water reaction as the basis of comparison. Therefore, the purpose of this study is first to establish a list of possible tube-to-tubesheet weld design configurations and to quantitatively assess their corresponding reliability against leaks. The reliability of different LMFBR steam generator designs against tube-to-tubesheet weld failure will be then established based on the design conditions summarized in Table 1.

Since most of the available failure experience of tube-to-tubesheet welds involve Inconel-600 fillet welds used in PWR plants, an upper bound and a most likely estimate of the failure rate will be established for this type of weld. However, as noted in Table 1, 2¼Cr-1Mo was selected as the material for the tube-to-tubesheet weld reliability study. Therefore, a comparitive review is made of the different mechanical properties and stress corrosion cracking resistance of the two materials in order to express quantitatively an upper bound as well as a most likely estimate of the failure rate of a 2¼Cr-1Mo fillet weld. To provide quantitative measures of the weld reliability, a failure mode and affects analysis (FMEA) is conducted to compare the risks of failure of the different weld types to that of the fillet weld. These values are then employed to establish the probabilities of failure of the different weld configurations through the use of a Fault Tree Analysis (FTA).

Table 1

1500 MW_e HOCKEY STICK STEAM GENERATOR

Description	Single Wall	Double Wall
No. of Loops in Plant	4	4
Module/Loop	2	3
Material	2¼Cr-1Mo	2¼Cr-Mo
Module Data		
Steam Temps., in/out, °F	480/707	480/708
Sodium Temps., in/out, °F	867/648	867/650
Tube OD/ID, inches	.750/.532	NA
Inner Tube OD/ID	NA	.625/.460
Outer Tube OD/ID	NA	.800/.625
Tube Number	889	793
Tube Lengths, Active Ft.	82	75
Pressure Drop, Steam, PSI	53	38.1
Pressure Drop, Sodium, PSI	4	8.2

II. REVIEW OF 2¼Cr-1Mo STEEL PROPERTIES [5]

As noted in Table 1, 2¼Cr-1Mo was selected as the material for the tube-to-tubesheet weld reliability study. Since it is expected that any weld failure would be as a result of fatigue crack propagation or stress corrosion cracking, we shall compare the resistance of 2¼Cr-1Mo to environmental attack as well as its mechanical properties to those of Inconel-600.

i) Environmental Compatibility

1) STRESS CORROSION CRACKING

In order to assess the stress corrosion cracking resistance of both materials for service in nuclear power plant environment, a literature survey[6] was conducted to establish their relative SCC resistance. 20% of the nuclear power plants surveyed show some form SCC. Inconel 600 experienced a higher incidence of SCC failure than 2¼Cr-1Mo for which no failures were observed. These occurrences were primarily attributed to deviations of established water chemistry. Impurities correlated with these failures were chloride, oxegyn or caustic. This survey was augmented by additional experimental programs to establish more accurately the relative SCC resistance of these materials.

The chloride stress corrosion cracking resistance of a number of materials (including weld joints) was investigaged in a program established by Oak Ridge at the Bartow Plant of Florida Power Corp.[7] . The tests consisted of cycling specimens of the various materials between 536°F and 797°F three times per week while injecting 10ppm sodium chloride and 20ppm oxygen. Consistent with the results reported in reference [5], about 33% of the Inconel-600 specimens failed. On the other hand, all the 2¼Cr-1Mo specimens showed total immunity to chloride stress corrosion cracking. The results of the failure history of the various materials in this environment are summarized in Table 2.

Tests were conducted at constant strain rates levels ranging from 10^{-3} to $1.2x10^{-1}$ per hour in 600°F, 1750 psi water contaminated with up to 5% concentration of N_aOH, to assess the propensity of these materials to caustic stress corrosion cracking. As noted in Table 3, Inconel 600 did not crack during relatively high exposure times and stress levels. 2¼Cr-1Mo specimens showed no inclination to cracking at exposure times four times that used for Inconel-600 specimens and at stress levels up to 2.8 times its yield stress at 600°F. In addition, it was observed that 2¼Cr-1Mo specimens were able to withstand exposure for several days in 600°F contaminated water with a 3% concentration of NaOH.

Therefore, the conclusions that can be drawn from this as well as other studies, e.g.,[8] is that 2¼Cr-1Mo is not prone to stress corrosion cracking in chloride, caustic contaminated aqueous or superheat environments showing a far larger resistance to failure when exposed to various off-chemistry environment than Inconel 600.

Table 2. Results of Chloride Stress Corrosion Tests

Alloy	Surface Condition	Number of Failures	Crack Initiation Time (weeks)
Inconel-600	Ground	4 of 6	1-12
	Ground & annealed	0 of 6	
	Ground, annealed & pickled	0 of 3	
2-1/4Cr-1Mo (SA-218-T22)	Ground	0 of 3	No cracks during 16-18 week exposure
	Ground & annealed	0 of 3	

Table 3. Summary of High Temperature Aqueous SCC Tests with 3% N_aOH

Alloy	Condition	Yield Strength, Ksi(MPa)	Applied Stress Ksi(MPa)	Hours	Result
Inconel-600	Annealed	36(248)	54(372)	350	No cracks
Inconel-600	and Sensitized	36(248)	54(372)	350	No cracks
2-1/4Cr-1Mo	Annealed	28(193)	44(303)	1450	No cracks
2-1/4Cr-1Mo	Annealed	28(193)	44(303)	1450	No cracks
2-1/4Cr-1Mo	Annealed	28(193)	56(386)	1450	No cracks
2-1/4Cr-1Mo	Annealed	28(193)	56(386)	1450	No cracks
2-1/4Cr-1Mo	Normalized and Tempered	65(448)	75(517)	1450	No cracks
2-1/4Cr-1Mo	Normalized and Tempered	65(448)	75(517)	1450	No cracks
2-1/4Cr-1Mo	Annealed and	77(531)	75(517)	1150	No cracks
2-1/4Cr-1Mo	Cold Worked 25%	77(531)	75(517)	1150	No cracks

2) WATER SIDE CORROSION

The behavior of both 2¼Cr-1Mo and Inconel 600 in a water environment is characterized by the formation of a fairly adherent chromium oxide acting as a barrier against material damage. The strength of this oxide barrier is dependent upon the amount of chromium content in the alloy and the operating temperatures. Studies carried out at temperatures ranging from 890-965°F

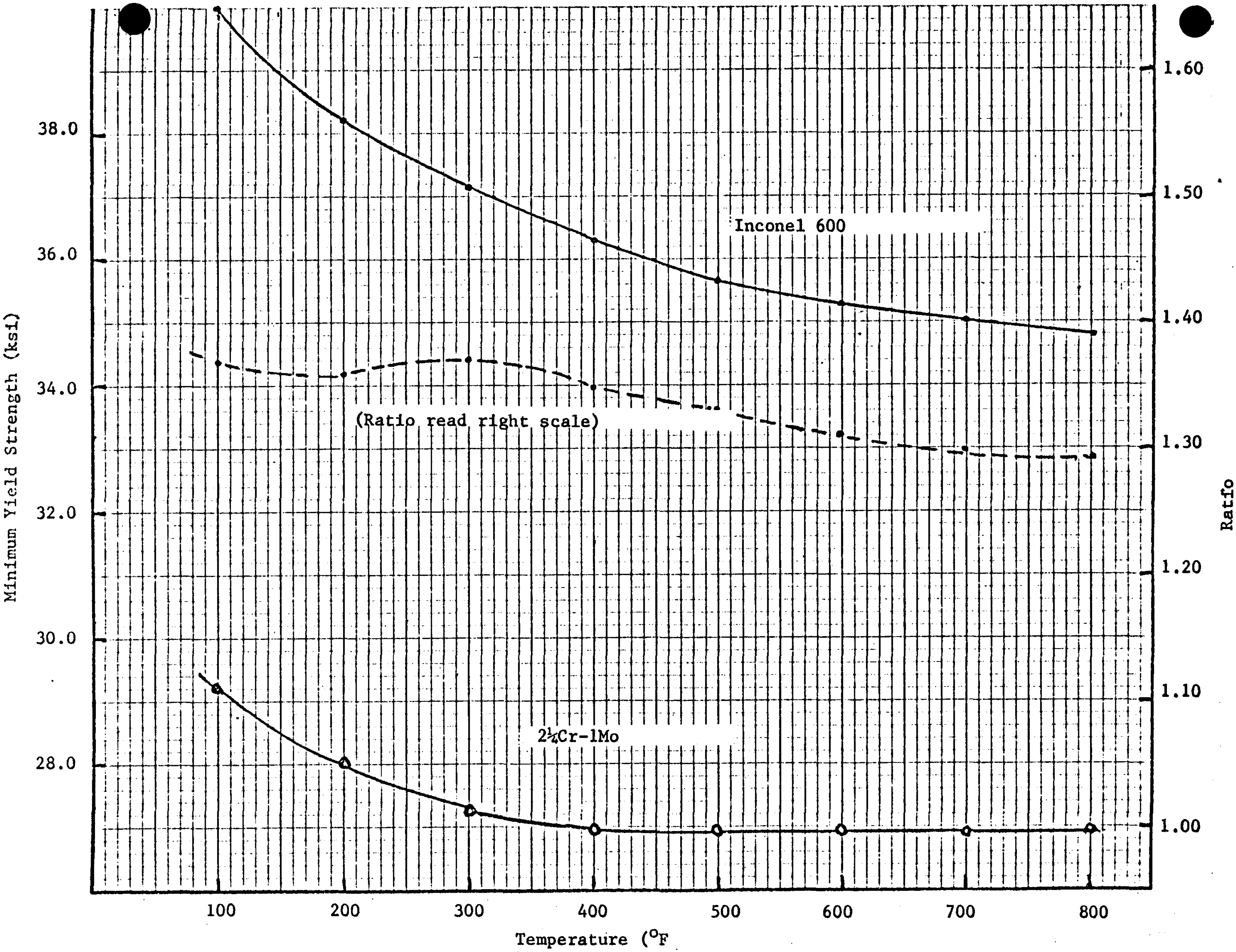


Fig. 1. Minimum Yield Strength vs. Temperature

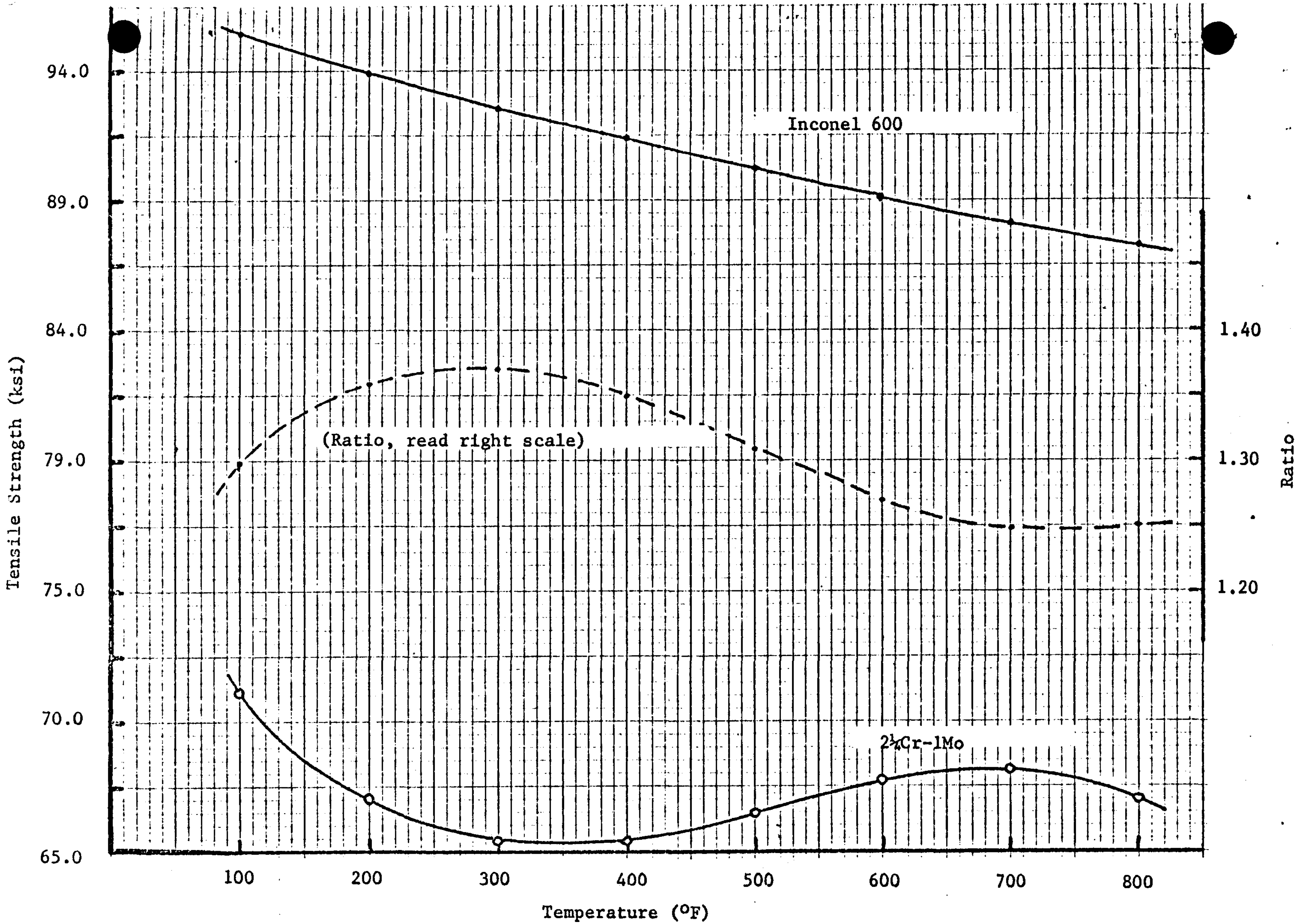


Fig. 2 Tensile Strength vs. Temperature

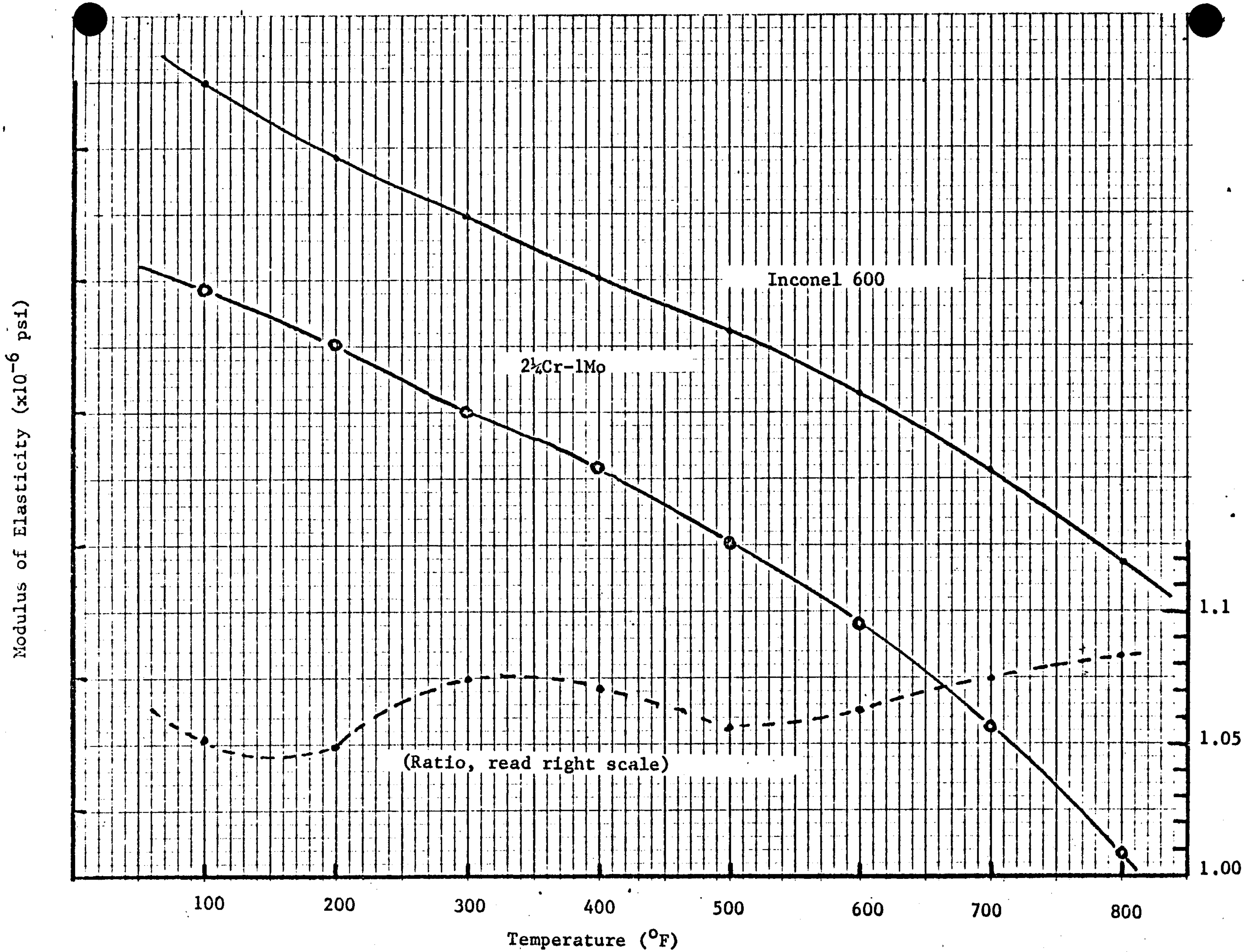


Fig. 3. Modulus of Elasticity vs. Temperature

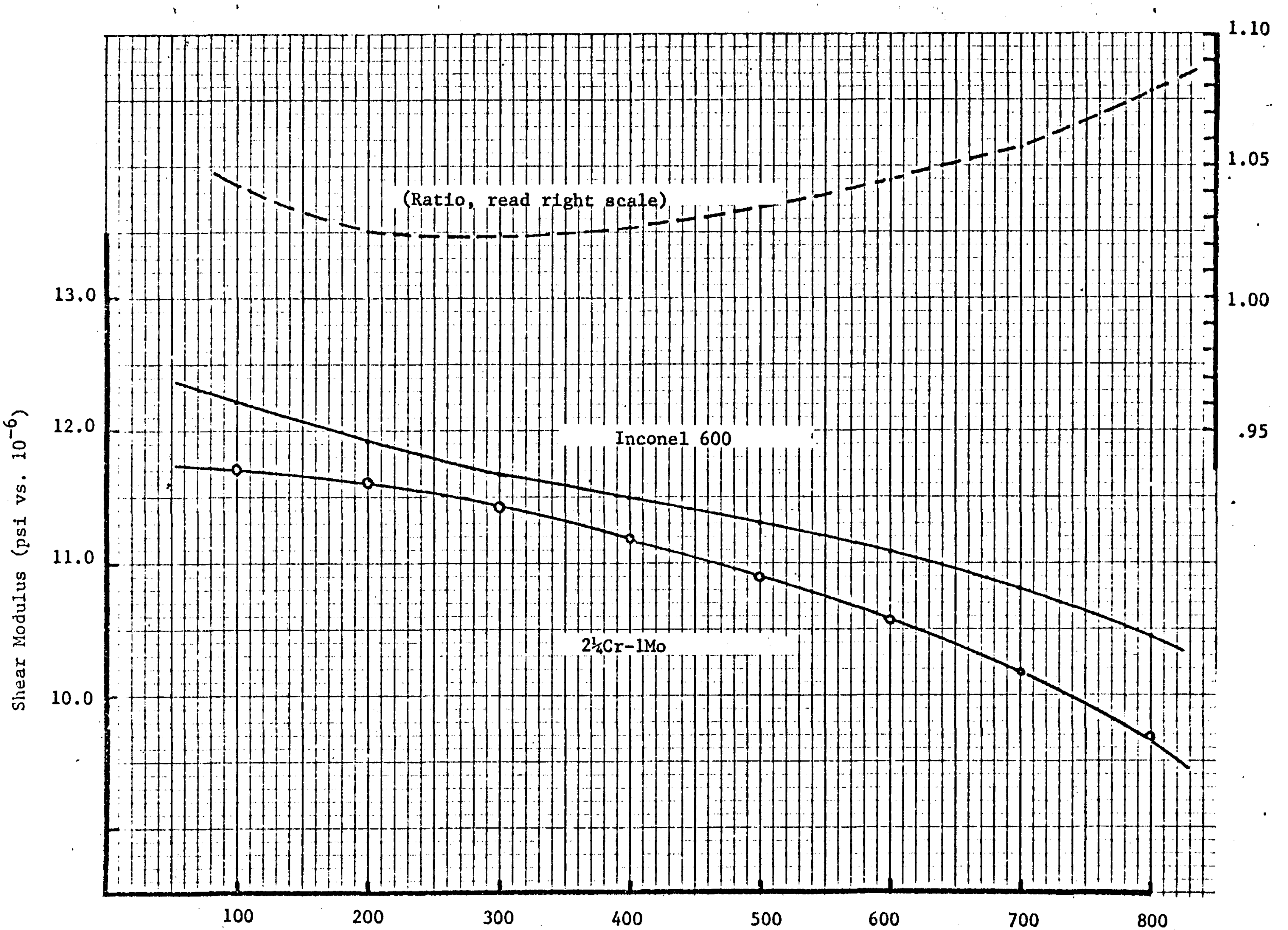


Fig. 4 Shear Modulus vs. Temperature

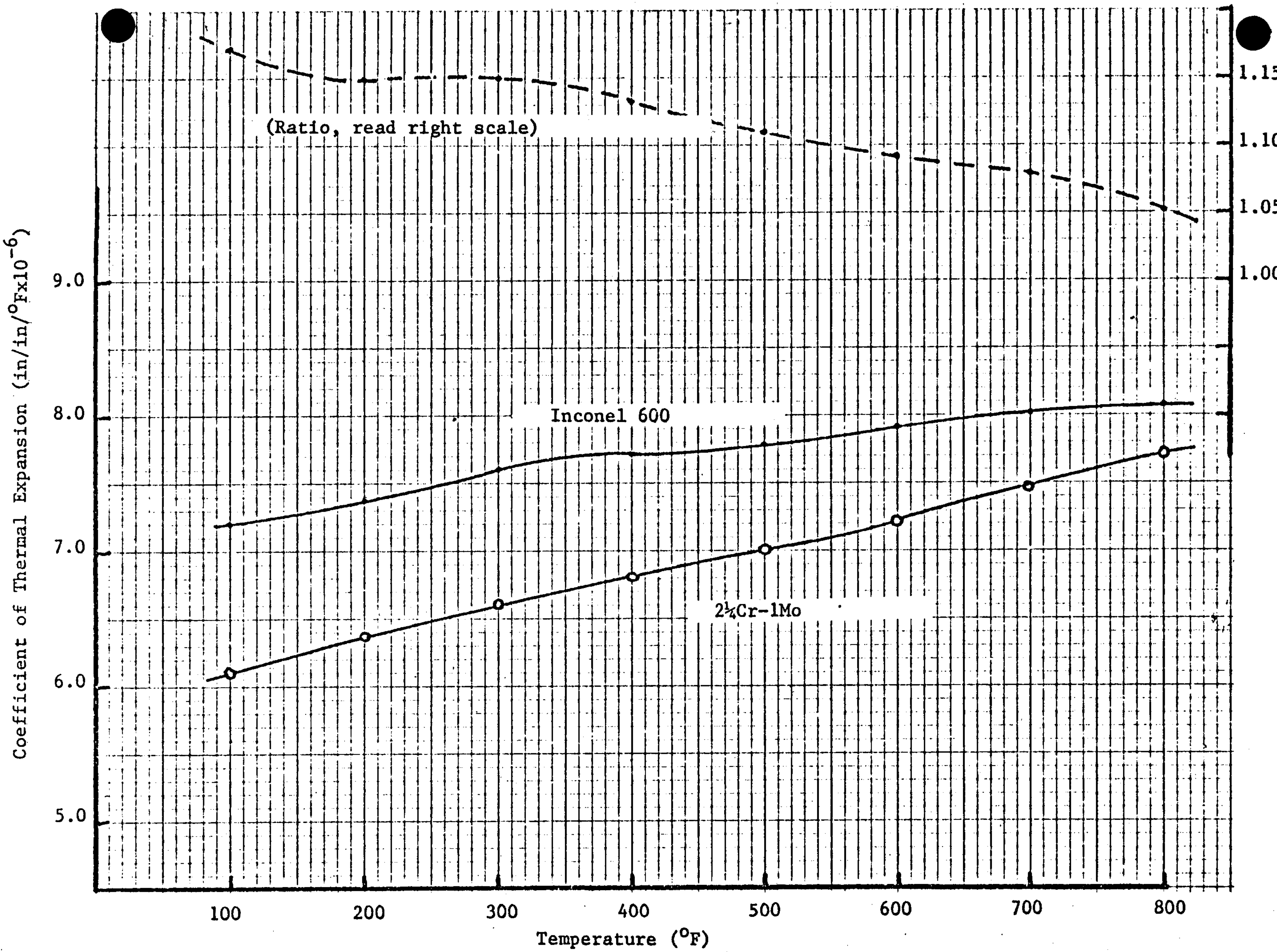


Fig. 5 Coefficient of Thermal Expansion vs. Temperature

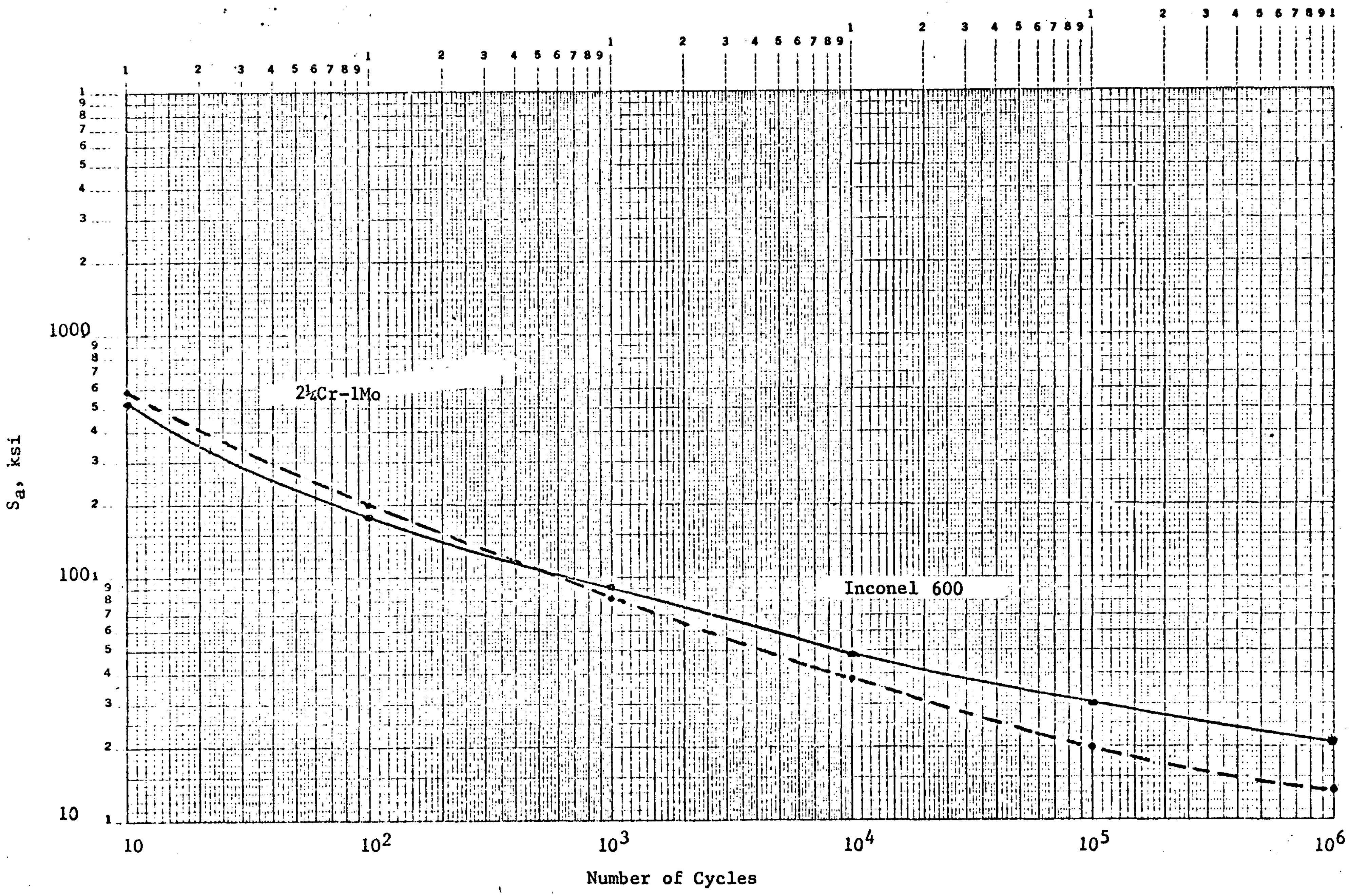


Fig. 6 Design Fatigue Curves at Room Temperature

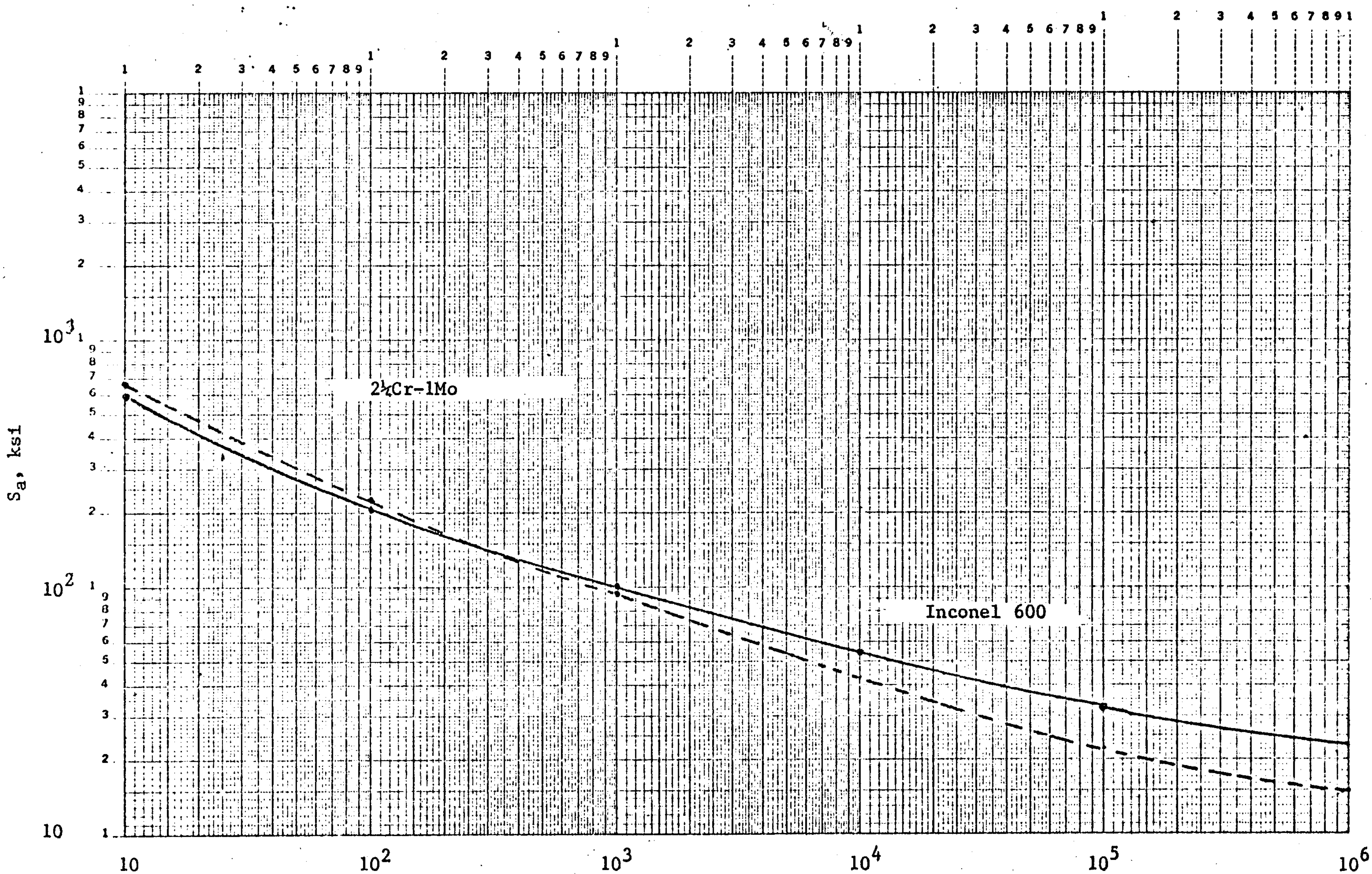


Fig. 7 Design Fatigue Curves at 700°F

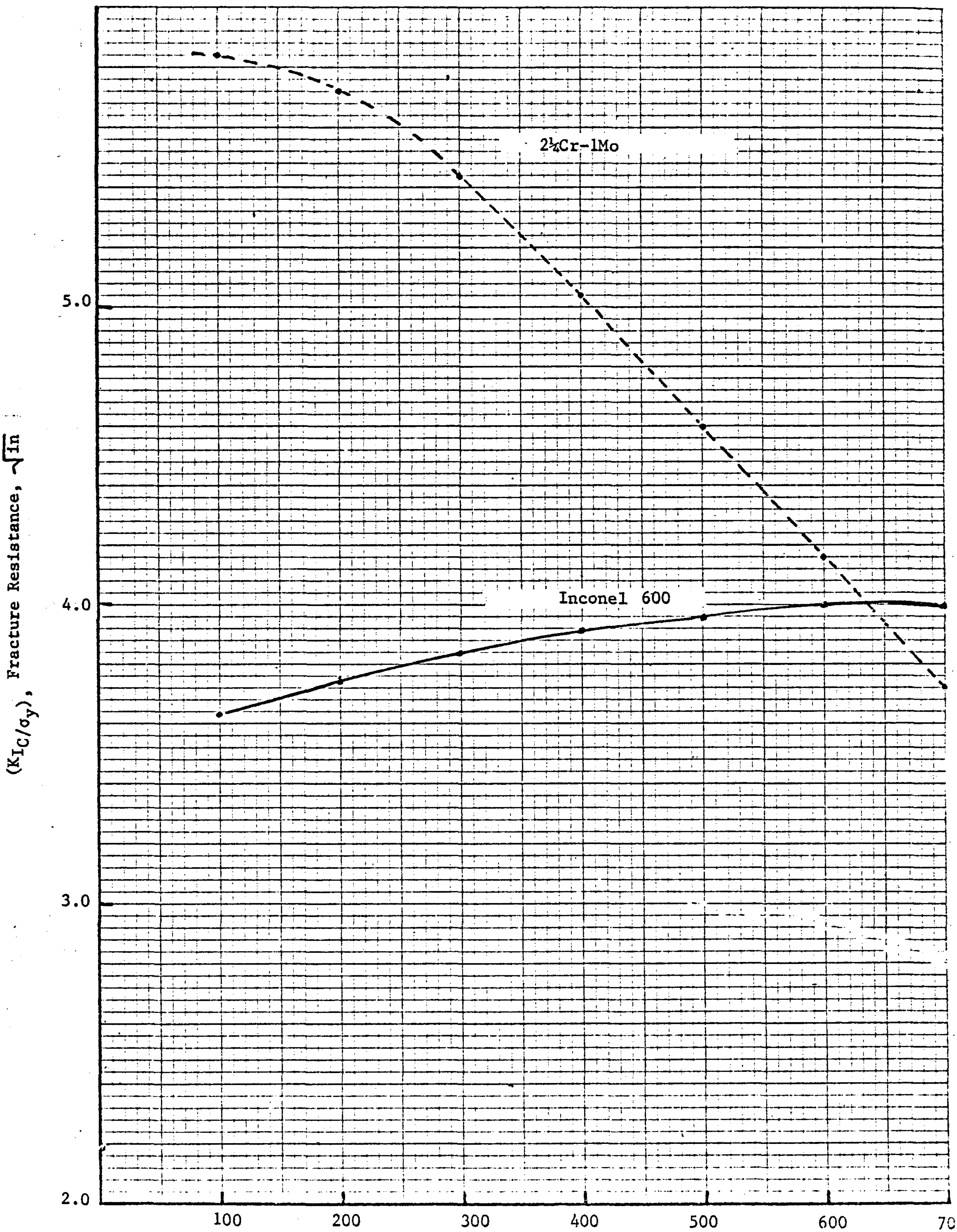
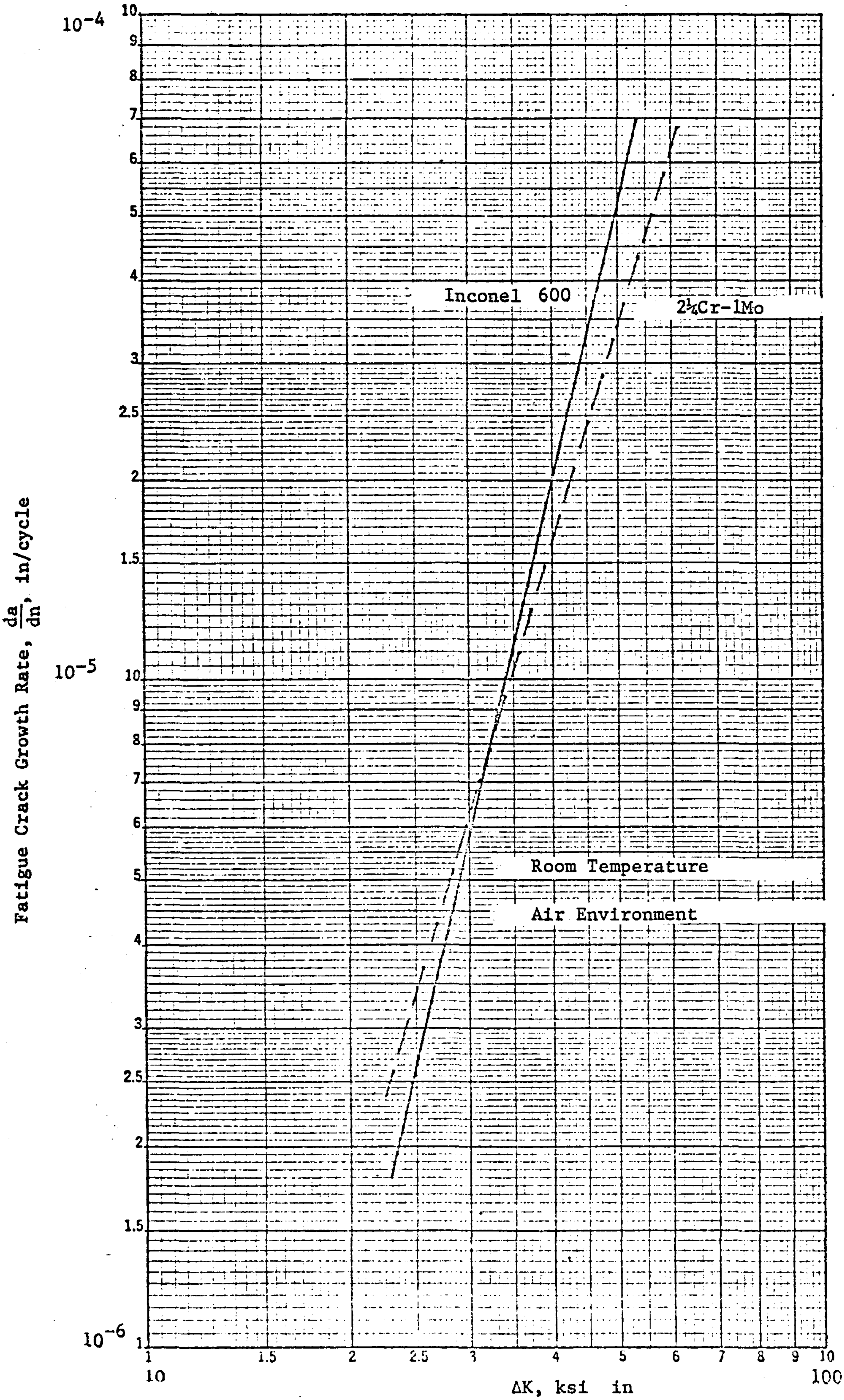


Fig. 8 Fracture Resistance vs. Temperature


Fatigue Crack Growth Rate, $\frac{da}{dn}$, in/cycle
10^{-4}
10^{-5}
10^{-6}
Inconel 600
$2\frac{1}{4}$Cr-1Mo
Room Temperature
Air Environment
10
100
ΔK, ksi in

predict a slight amount of metal loss for 2¼Cr-1Mo material during 30 years [9]. On the other hand no corrosion allowances are established for Inconel 600 owing to its higher chromium content.

3) SODIUM SIDE CORROSION

A number of studies carried out to establish the corrosive characteristics of a sodium environment [10,11] tend to indicate that for at least the temperatures of interest, 2¼Cr-1Mo is unaffected by sodium corrosion.

ii) Mechanical Properties

From references [12,13,14,15,16] the significant temperature dependent of Inconel 600 can be compared to those of 2¼Cr-1Mo. This comparison is summarized in Figs. 1-9 where each figure represents a different mechanical property plotted as a function of temperature for each material. Also shown on Figure 1-5 is a plot of the ratio of the different values of the mechanical properties for each material as a function of temperature.

Table 4

SUMMARY OF MECHANICAL PROPERTIES FOR INCONEL-600 and 2¼Cr-1Mo @ ROOM TEMPERATURE

Property	Inconel-600	2¼Cr-1Mo
Total Elongation, %	40	33
Reduction of Area, %	55	71
Modulus of Elasticity, psi	$32x10^6$	$30x10^6$
Yield Stress, psi	$40x10^3$	$30x10^3$
Ultimate Tensile Stress, psi	$95x10^3$	$71x10^3$
Fracture Toughness, ksi in	145	170
Shear Modulus, psi	$12.2x10^6$	$11.7x10^6$

Table 5

SUMMARY OF MECHANICAL PROPERTIES FOR
2¼Cr-1Mo AND INCONEL-600 @ 800°F

Property	Inconel-600	2¼Cr-1Mo
Total Elongation, %	61	22.6%
Modulus of Elasticity, psi	$28x10^6$	$25.7x10^6$
Yield Stress, psi	$35x10^3$	$27.1x10^3$
Ultimate Tensile Stress, psi	$87x10^3$	$67.x10^3$
Shear Modulus, psi	$10.8x10^6$	$10.2x10^6$
Reduction of Area, %	56.6	68.5
Fracture Toughness, ksi in	140	100
Coeff. of Thermal Expansion	$8.1x10^{-6}$	$7.8x10^{-6}$

From sections II(i) and II(ii) it can be concluded that Inconel-600 is a stronger material (approximately 35% and 30% higher yield and ultimate tensile strength respectively). On the other hand in order to compare the fracture resistance of engineering materials, the plane strain crack size factor ($\frac{K_{Ic}}{\sigma_y}$) provides a measure of toughness that accounts in a single parameter for the interaction of K_{IC} and strength on crack size tolerance [17]. Therefore, the material with the highest ($\frac{K_{Ic}}{\sigma_y}$) ratio can be expected to be the tougher material for a given application [18]. It is shown in Fig. 8 that 2¼Cr-1Mo is more crack resistance than Inconel 600 for temperatures lower than 635 °F at which point Inconel 600 fracture resistance is almost a constant while 2¼Cr-1Mo fracture toughness drops further. However, the stress corrosion cracking resistance of 2¼Cr-1Mo is far superior to that of Inconel 600 for a number of commonly found contaminants. Therefore it can be concluded that these two materials are of comparable quality as tube-to-tubesheet weld materials for LMFBR application.

III. POSSIBLE WELD CONFIGURATIONS

i) Welding Fabrication and Inspection Procedures

It is our contention that reliable welds having good repeatibility can only be accomplished by an automatic process. The automatic gas tungsten arc weld process or TIG welding with or without cold wire feed appears to be the most reliable of all automatic fabrication process. The welding process (GTAW) can either be standard or pulsed. When properly performed, the weld puddle is protected from environmental contamination by an inert gas (argon or helium) to diminish the possibility of porosity in the weld area which constitutes the most prevalent defect in tube-to-tubesheet joints.

The quality of weldments can be assessed through a variety of non-destructive examinations. Typical examinations include a visual inspection with magnification ranging from 2X-5X. This is followed by a dye-penetrant (PT) or a magnetic particle (MT) to identify surface defects. To uncover potentially serious sub-surface defects, a volumetric examination can be performed which includes radiography (RT) or ultrasonics (UT) testing. In addition while still in its development stages, acoustic emission offers considerable promise as an effective volumetric inspection technique. Finally, the weld is examined for leakage by subjecting the joint to a gas pressure test to identify critical size sub-surface defects and/or defects which extend through the weld cross-section.

None of these testing techniques by itself provides sufficient assurance of the quality of the weld. Rather it must be acknowledged that these are complementary techniques and that each method has its advantage and limitations. In general, it can be stated that PT constitutes a very effective technique for surface evaluation provided that the inspector has direct access to the surface being examined. If the surface cannot be directly examined but requires additional instrumentation for evaluating the observations (such as a boroscope) as would be the case for the internal bore butt weld, the sensitivity of the technique is reduced. Both RT and UT are suitable non-destructive examination techniques for sub-surface defects. Again, the effectiveness of the test is very much related to the accessibility of the surface being examined.

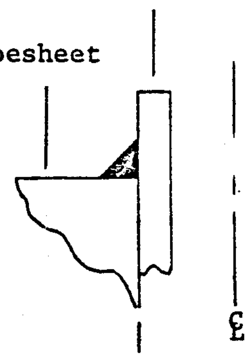
ii) Weld Types

Weld types shown present two welding concepts, i.e.,

1. Direct weldment of the tube to the tubesheet using fillet or recess weld junctions,
2. Weldment of the tube to a machined boss using fillet or butt weld junctions.

Five such weld types are shown. These welds form the nuclei for the compilation of the weld configurations presented in Section iii.

1) Fillet Weld (Tube-to-Tubesheet)



Design Features

Direct weldment of the tube-to-tubesheet using a fillet weld.

Advantage - manufacturing ease

Disadvantage - crevice, lack of volumetric inspection.

Fabrication

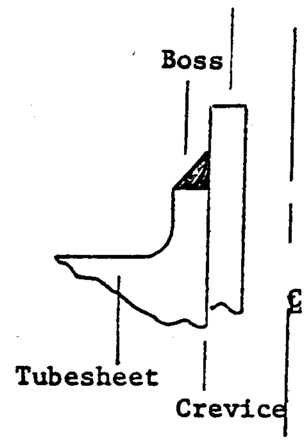
The welding is performed through an automatic GTAW process consisting of an initial seal pass which is inspected and followed by a cold wire feed pass. The proper tungsten arc height, electrode size and angle, trail angle, rotation diameter, wire feed angles and amperage setting could be established following extensive laboratory investigation.

Inspection

Following the seal pass welding procedure, the welds are visually examined with 5X magnification and the defects, if any, removed. Following the filler pass welding procedure, the fillets are visually examined by magnification for defects. This is followed by a dye penetrant inspection. In the event of fillet undercut, fillet surface rippling and fillet toe irregularities, these conditions are rejectable only if they cause dye penetrant indications. Defects and rejectable indications, not all found by any one inspection method, are defined as follows:

a. porosity
b. lack of fusion
c. cracks
d. tungsten inclusions

2) Fillet Weld (Tube-to-Boss)



Design Features

Weldment of the tube to a machined boss using a fillet weld.

Advantage - welding ease, volumetric inspection

Disadvantage - cost in machining, crevice.

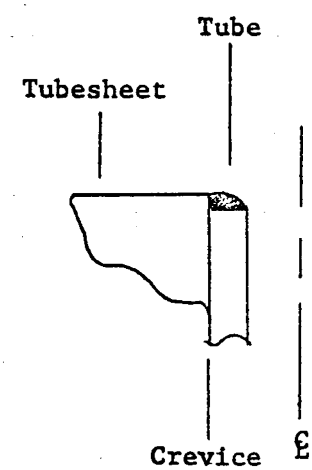
Fabrication

Similar to (1) except that the tube is welded to a machined boss on the tubesheet.

Inspection

Similar to (1) except that welding to the boss a distance from the cladded surface of the tubesheet permits complete radiographic inspection.

3) Recessed Weld (Tube-to-Tubesheet)



Design Features

Direct weldment of the tube-to-the-tubesheet using a recessed weld

Advantage - manufacturing ease

Disadvantage - crevice, lacks volumetric inspection

Fabrication

Welding is accomplished through an argon shielded autogeneous GTAW weld pass resulting in a weld consisting primarily of re-fused Inconel cladding. The welds (all configurations mentioned in this report) should be made with a minimum preheat of 300°F and a maximum interpass temperature of 500°F. A post weld heat treatment is recommended. The welding procedure should insure a minimum of roll over. After welding, the buildup is ground or machined to size and inspected as noted below.

Inspection

The recessed welds must be examined for defect as follows:

a) The weld joint is visually inspected (using workmanship samples as aid) for gross defects such as lack of fusion (a portion of the top of the tube showing) and for proper size and contour. Unacceptable roll-over is detected through the use of plug gage.

b) Following (a) the weld is dye-penetrant inspected and finally a gas leak test is performed.

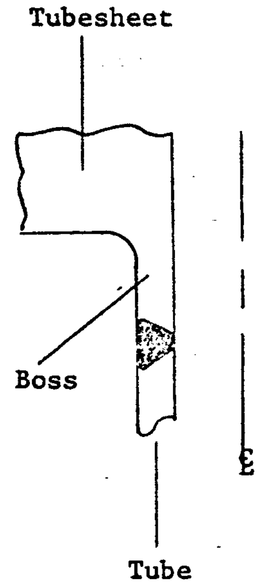
4) Outside Diameter Butt Weld (Tube-to-Boss)

Design Features

Direct weldment of the tube to a machined boss.

Advantage - elimination of structural discontinuities in the weld zone

Disadvantage - difficulty in making the external weld, cost of machining the boss.



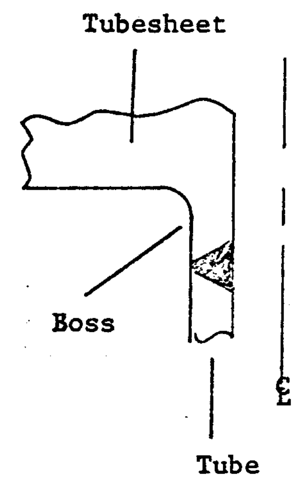
Fabrication

Welding is performed using an automatic gas tungsten arc welding process. The external bore tube-to-tubesheet welding process has the options of (a) no filler wire, (b) filler wire, or (c) a filler metal insert. The tubes should be welded one row at a time in order to provide accessibility for inspection and in order to accomplish any necessary repairs.

Inspection

After welding each row of tubes, a visual examination will be conducted on each tube-to-tubesheet weld followed by a dye penetrant inspection with the subsequent removal of defects. This O.D. dye penetrant inspection is used mainly for the detection of surface porosity Another dye penetrant inspection will be performed on the internal diameter for porosity and lack of fusion. However, the accuracy of the I.D. dye penetrant test will not be as great as the O.D. test because the test surface must be viewed through a borescope. A radiographic inspection will be performed with the film on the O.D. of the tube and the x-ray source on the inside. The x-ray inspection should detect any critical size internal defects which will then be removed and a weld repair performed. These inspections are followed by a gas leak test and finally a hydrotest is performed.

5) Internal Bore Butt Weld (Tube-to-Boss)



Design Features

Direct weldment of the tube to a machined boss.

- Advantage - elimination of structural discontinuities in the weld zone, allows volumetric inspection
- Disadvantage - cost of machining boss.

Fabrication

Welding is performed using an internal automatic gas tungsten-arc welding process. The three options of (a) No filler wire, (b) filler wire or (c) a filler metal insert mentioned in the outside diameter butt welding are also available for internal bore welding. As in outside bore welding, the tubes should be welded one row at a time to provide the necessary accessibility for inspection and repair. However, this welding process lacks the advantage of the external bore welding process of allowing the operator to visually check the positioning of the welding head.

Inspection

Each row of tube-to-tubesheet welds will receive a visual examination followed by a dye penetrant inspection on the outside diameter of the tube. This inspection procedure should be excellent for detecting any surface porosity and lack of fusion. Another dye penetrant inspection procedure may be performed on the internal diameter, but the sensitivity of this inspection will not be as great as the O.D. test because the test surface must be evaluated through a boroscope. Any defects found as a result of these inspections are removed and repaired.

These inspection processes will be followed by a radiographic examination of the welds having the film on the outside diameter of the tube and the x-ray source inside the tube. Should this radiographic inspection uncover any critical internal defect in the weldments, they are then removed and the weld repaired. This procedure is then followed by a gas leak test and a hydrotest. If any defective welds are found as a result of these tests, the welds will be repaired.

iii) Welding Configurations

The five weld types described in the preceding section can be combined in various ways to form different configurations applicable to either single or double tubesheet steam generator designs. The different weld configurations illustrated in Figs. 10 represent six of the most practical designs. Those dropped from further evaluation were done so for the following reasons,

1. similarity to a configuration selected for evaluation
2. obvious structural deficiency and,
3. fabrication difficulty.

Weld Configuration	Weld Types	Tubesheet
A	1,2	Single Double

Configuration used in the WTD SSGM

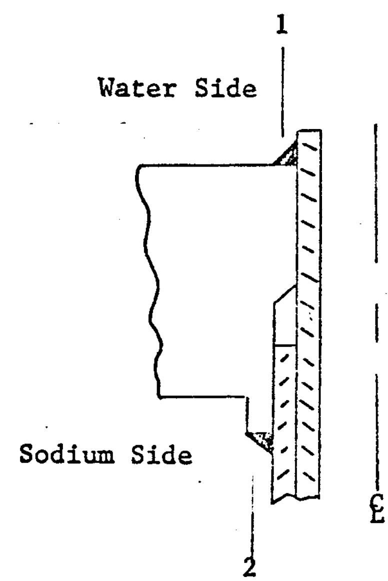
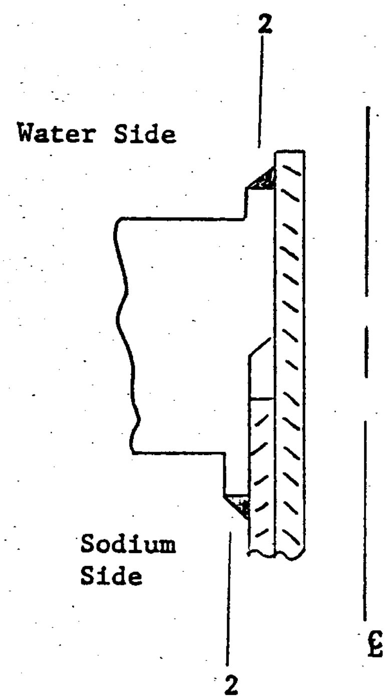


Fig. 10 Different Tube-to-Tubesheet Weld Configurations

Weld Configuration	Weld Types	Tubesheet
B	2	Single Double
C	2,5	Single Double

B: Configuration proposed use in the WTD J-module design



C: Use of weld type 5 for the outer tube destroys leak detection capability

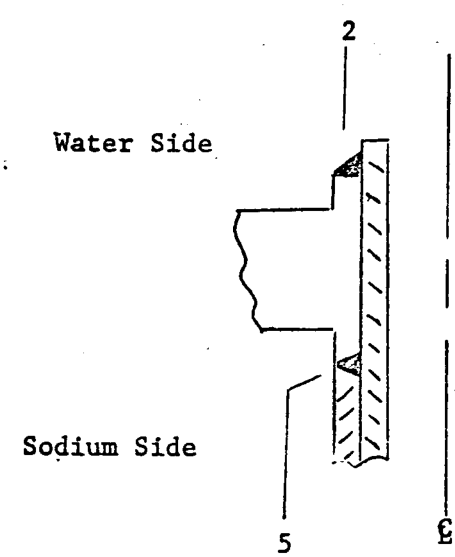
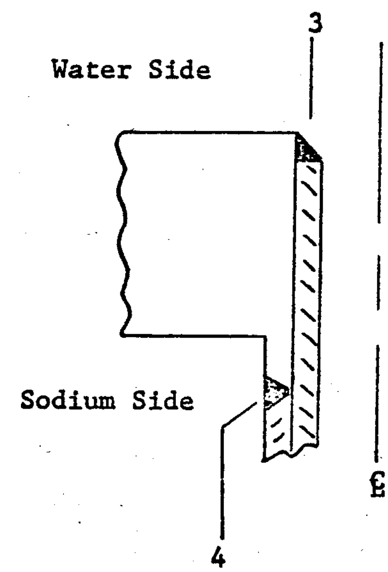


Fig. 10 (Cont.'d)

Weld Configuration	Weld Types	Tubesheet
D	3,4	Single Double

Use of weld type 4 on outer tube destroys leak detection capability



Weld Configuration	Weld Types	Tubesheet
E	2	Double

Similar to the EBR-II weld configuration

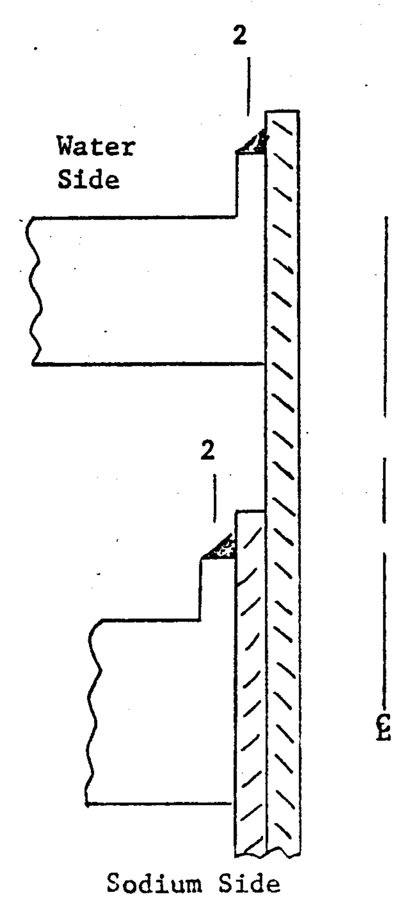


Fig. 10 (Cont.'d)

Weld Configuration	Weld Types	Tubesheet
F	2	Single

Configuration reliability is equal to that of a single tube design using weld type 2.

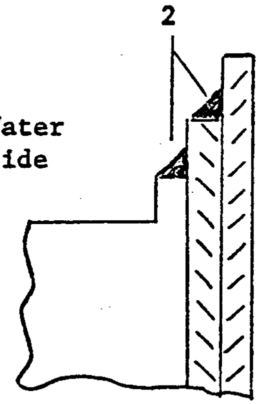


Fig. 10 (Cont.'d)

IV. WELD RELIABILITY

i) Introduction

The reliability of a component can be defined as the probability that the component has not failed from carrying out its intended function for a specific time, i.e., from time zero up to time of interest. Hence, the reliability is a function of time which can be expressed mathematically as [19]:

$$R(t) = P\{T>t\} = e^{-\int_0^t \lambda(\tau)d\tau} \tag{1}$$

where R(t) is the reliability function of the component.
T is the time to failure of the component.
$\lambda(\tau)$ is the failure rate of the component

Therefore, if we know the failure rate of a component we can determine its reliability function. If, however, the process in question satisfies the axioms which define a homogeneous Poisson Process *, a constant failure rate may be assumed and the reliability function of the component becomes [20]:

$$R(t) = e^{-\lambda t} \tag{2}$$

If the axioms defining a homogeneous process are not satisfied, the simplification of constant failure rate is not applicable and the failure rate must be considered a function of time.

It should be obvious from either Eq. (1) or (2) that the determination of the component failure rate constitutes the critical item in establishing measures of component reliability. This parameter inherent to a particular design under specified conditions of operation is expressed in terms of some unit of time (hourly, daily, yearly, etc.). Owing to the significance of this parameter in structural reliability and for sakes of completeness, effort will be spent in this section to describe how it is determined.

In reference [4], it is demonstrated that a point estimate of the failure rate of a component in an interval of time Δt_i is given by

$$\lambda_i = \frac{1}{N_i} \frac{\Delta N_i}{\Delta t_i} = \hat{\lambda}_i \tag{3}$$

* See Appendix I

where N_i is the number of items at the beginning of the interval and ΔN_i is the number of items failing during this interval. Under the assumption of constant failure rate, the point estimate $\hat{\lambda}_i$ becomes the failure rate of the process.

Basically, there are three ways to estimate the failure rate of a component:

1) Run tests
2) Use data from field units
3) Estimate from experience

Clearly the most accurate procedure consists of a test program since this will insure that the component and operating environment are identical to the particular case of interest. Unfortunately, this approach can result in considerable expense and although is the only alternative in certain occasions, its repeated use should be discouraged.

A second approach consists of accumulating data from operating units. As it will be shown, it is not necessary for the data to include a number of "failures"; information on the number of components in service and number of hours of successful operation can be used to estimate a conservative failure rate of the component.

The third way to estimate failure rate data is far more useful than it would appear at first glance. An "educated guess" based on good sound engineering judgment can result in an excellent first order approximation. Furthermore, if available data exist of a similar component, i.e., similar geometry and loading conditions, inference can be drawn from its results to more strongly substantiate or improve the educated guess. As failure data becomes available, Bayesian Methods * can be applied to refine the initial estimate.

Up to this point an attempt has been made to estimate the failure rate of a component through a single statistic resulting in a point estimate of this parameter. Since the failure rate is an intrinsic characteristic of the component for given operational and environmental conditions, point estimates may or may not be very close to the actual value of the parameter. Therefore, this estimate would be more significant if one knew the degree of uncertainty

* See Appendix II

in the estimate as expressed as a confidence interval or confidence level. As described in reference [4], an upper bound for the failure rate at a desired confidence level K is given by

$$\lambda_u = \frac{\chi^2_{K,2r+2}}{2nt} \qquad (4)$$

where n = number of components considered

t = total time of operation of components

r = number of failures observed

ν = number of degrees of freedom = 2r+2

ii) Reference Weld Configuration

As a point of reference on which to establish quantitative measures of tube-to-tubesheet weld reliabilities for different weld configurations, the reliability of the fillet weld concept will be established. Since this weld configuration is the reference concept, the fabrication and inspection procedures, previously described, as well as the repair method are summarized below.

1) FABRICATION

The welding is performed through an automatic GTAW process consisting of an initial seal pass and followed by a cold wire feed pass. The proper tungsten arc height, electrode size and angle, trail angle, rotation diameter, wire feed angles and amperage setting have been established following extensive laboratory and actual fabrication welding experience.

2) INSPECTION

Following the seal pass welding procedure, the welds are visually examined with 5X magnification and the defects, if any, corrected. Following the filler pass welding procedure, the fillets are thoroughly cleaned by stainless steel brushes. After brushing the welds are visually examined by magnification for defects (cracks, porosity) as well as size and contour of tube weld. This is followed by a dye penetrant inspection. In the event of fillet undercut, fillet surface rippling and fillet toe irregularities, these conditions are rejectable only if they cause dye penetrant indications. Defects and rejectable indications are defined as follows:

a. porosity
b. lack of fusion
c. cracks
d. tungsten inclusions

Following the repair of defective joints, the tube welds are inspected by a gas pressure test of the secondary side. All weld leaks are then repaired and reinspected.

3) REPAIRS

All defects (voids, cracks, porosity) are removed by grinding. The ground areas are then visually examined by magnification to ascertain complete removal of the defects. Lack of washup is repaired by re-welding.

4) PROOF TESTING

The welds are initially subjected to a hydrostatic pressure of magnitude 25% higher than that during steady state operating conditions.

5) FAILURE RATES

Experience with approximately 208,000 Inconel 600 tube-to-tubesheet welds operating for about 45 years has produced one failure. Although, there has been a very small number of joints repaired during the fabrication process as outlined in the previous section, evidently the defects were properly corrected as evidenced by lack of PT and gas leak indications as well as the almost failure free service experience. Therefore, assuming this to represent a homogeneous Poisson process, an upper bound of the failure rate can be estimated at a 99% confidence level from Eq. (4).

Hence,

$$\lambda_u = (14.86)/2(45)(208000) = 7.94 \times 10^{-7}\ \text{year}^{-1} \quad (5a)$$

On the other hand, a maximum likelihood estimate for the fillet weld failure rate is given by the point estimate

$$\lambda_o = 1/(45)(208000) = 1.07 \times 10^{-7}\ \text{year}^{-1} \quad (5b)$$

This weld operates during steady state conditions under a primary fluid pressure of 2250 psi at approximately 620°F and under a secondary fluid pressure of 1200 psi at 540°F. In order to relate the failure rates obtained in Eq. (5) for an Inconel-600 fillet weld to a similar weld fabricated of 2¼Cr-1Mo and operating at conditions specified in Table 1, it will be assumed that the ratio of the failure rates for the two materials is a function of several parameters related to the mechanical properties of the two materials and the operating conditions, i.e.,

$$\lambda_r = f\left\{\left(\alpha\Delta T\right)_r, \left(\frac{1}{\frac{K_{IC}}{\sigma_y}}\right)_r, \left(\frac{da}{dN}\right)_r, \left(\frac{S}{S_m}\right)_r\right\} \tag{6a}$$

where $$X_r = \frac{\text{value of X for 2¼Cr-1Mo at Temperature T}}{\text{value of X for Inconel at Temperature T}} \tag{6b}$$

Therefore,

$$\lambda_{2\frac{1}{4}Cr-1Mo} = \left\{\left(\alpha\Delta T\right)_r \times \left(\frac{1}{\frac{K_{IC}}{\sigma_y}}\right)_r \times \left(\frac{da}{dN}\right)_r \times \left(\frac{S}{S_m}\right)_r\right\} \lambda_{Inconel} \tag{7}$$

The parameters listed in Eq. (6a) reflect our belief that weld failure is primarily a fatigue crack propagation phenomena. Thus, since the stress intensities responsible for fatigue failure consist of secondary and peak stress components which are directly related to thermal gradient, the term $\alpha\Delta T$ is considered in Eq. (6a). Similarly, the fracture resistance of the material (K_{Ic}/σ_y) and the crack growth rate are parameters which are directly related to fatigue failure and hence are included in Eq. (7). Finally, in order to account for the material strength, a parameter involving the ratio of the applied stress intensity S to the allowable stress Sm is considered in Eq. (6a). However, it can be argued that if the joint is to be designed efficiently, the applied stress should be very close to its allowable value. Therefore, for computational purposes (S/Sm) will be taken as unity.

ΔT will be chosen conservatively as the difference between sodium and steam fluid temperatures. This would constitute a reasonable estimate if the fillet weld is located in the sodium side of the tubesheet. If in the other hand, the fillet weld is in the steam side, the thermal gradient will certainly be overestimated. However, for conservatism ΔT will be chosen as the difference between sodium and steam fluid temperatures irregardless of the location of the fillet weld. The temperature at which the parameters of Eq. (7) are to be evaluated will be chosen to be the average of the secondary and primary fluid temperature.

Therefore, from Table 1, $\Delta T = 168^oF$, $T_{ave} = 564^oF$ at the water inlet tubesheet and $\Delta T = 160^oF$, $T_{ave} = 787^oF$ at the steam outlet tubesheet. Therefore, for conservatism it will be assumed that $\Delta T = 170^oF$, $T_{ave} = 800^oF$. Since for the PWR Inconel-600 fillet weld $\Delta T = 80^oF$, $T_{ave} = 580^oF$ it can be established from Figs. 5, 8 and 9 and Eq. (5a) that a conservative estimate of the failure rate of the 2¼Cr-1Mo fillet weld operating under conditions specified in Table 1 is

$$\lambda_u = \left(\frac{7.7 \times 170}{7.9 \times 80}\right) \times \left(\frac{4.00}{3.28}\right) \times (\sim 1.0) \times (\sim 1.0)\ (7.94 \times 10^{-7})$$

$$\lambda_u = 2.0 \times 10^{-6}\ \text{year}^{-1} \tag{8a}$$

To establish a most likely estimate it can be argued that although Inconel-600 is a stronger material that 2¼Cr-1Mo (~30% higher yield and ultimate stresses) the fracture resistance as well as the crack growth rate of both materials is almost identical. Furthermore, although difficult to quantify the stress corrosion resistance of 2¼ Cr - 1 Mo against various contaminants appears to be superior to that of Inconel - 600. In addition, it can be argued that since the allowable stress intensity of 2½Cr-1Mo is approximately 50% lesser than that of Inconel-600 for the temperatures of interest, if the joint is designed efficiently, it is expected that the Inconel-600 weld will be subjected to a higher stress. This would imply a higher stress intensity factor K_I and since the crack growth rate of both material is approximately the same, one should expect earlier failures in the Inconel-600 weld. Therefore, to establish the desired range of failure probabilities of the different weld configurations, the most likely estimate will be established by that given in Eq. (5b), i.e., the failure rate of the 2½Cr-1Mo fillet weld will be considered equal to that for Inconel-600. Thus,

$$\lambda_o = 1.07 \times 10^{-7}\ \text{year}^{-1}$$

6) RELIABILITY OF SINGLE VS. DOUBLE PASS WELDS

As noted in the previous section, the reference weld configuration to be employed to quantify the failure rates of the different tube-to-tubesheet weld designs is a fillet weld. The fabrication procedure for this weld consists of two passes. The first one is an autogeneous seal pass which is followed by a wire pass. WTD experience indicates that the most prevalent defect in either weld pass is porosity commonly caused by lack of cleanliness. Our experience further indicates that if porosity is present after the seal pass, the second pass tends to redistribute its location but does not eliminate it as shown in Fig. 11.

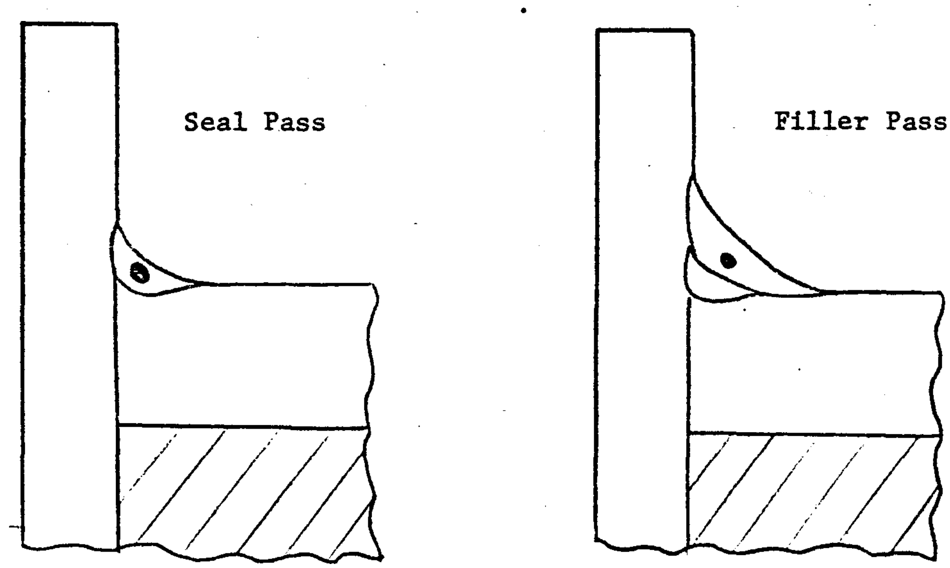


Fig. 11 Propagation of Porosity in a Double Pass Fillet Weld

However, since the porosity tends to settle in the center of the weld metal, the reliability of the multiple pass weld tends to be superior to the single pass weld due to the increase of the leak path dimension. WTD experiments with single pass autogeneous welds vs. double pass fillet welds conclusively prove this assumption.

iii) Failure Rates of Different Weld Configurations, FMEA

As noted previously, estimates of structural reliability are quantitative measures of the ability of a structure to operate safety for a given period of time against a particular failure mode. These values are not absolute numbers, rather they represent relative measures of structural reliability compared to a reference design. In this study, the tube-to-tubesheet fillet weld is employed as the reference configuration and the failure rates for the different weld configurations are then compared to it. One standard method is the use of Failure Mode and Effects Analysis Techniques (FMEA)[22] to compare qualitatively the reliability of the different weld configurations and then by employing the quantiative measure of reliability of the reference concept, the failure rates of the different weld configurations can be estimated quantitatively

A general FMEA is shown in Table 6. From this table it can be seen that by far the most prevalent failure mode is tube-to-tubesheet weld leakage which either leads into the problem of loss of unit availability as a result of possible plant shutdown for weld repair or loss of both unit reliability and availability in the event of a N_a-H_2O reaction. In general, leakage is the result of propagation of sub-critical size defects in the weld metal as a result of either inadequate or insufficient inspection procedures or failure of inspector to identify a detectable defect. The most common type of defects present in tube-to-tubesheet welds are:

a) porosity
b) lack of fusion
c) cracks
d) tungsten inclusions

In order to estimate the failure rates for the different weld types, it is necessary to establish for each joint design, based on an arbitrary scale of 1 through 10, the possibility of encountering a defect having a size which would result in tube-to-tubesheet weld leakage. The larger the number used in the FMEA, the greater the risk of failure. Similarly it is necessary to estimate the relative probability of detecting the critical flaw size by available NDT techniques. These values will be established relative to the

Table 6. General FMEA of Tube-to-Tubesheet Weld

Part Name	Function of Part	Failure Modes	Failure Causes	P	C	Corrective Action
Tube-to-Tubesheet Weld	Maintain Boundary Integrity	Exceed Design Limits	1. Excessive Mechanical and Thermal Loads 2. Under Design 3. Substandard Weld Material 4. Fatigue	1	1	Re-Design
		Catastrophic Failure	1. Large Undetected Weld Defect or Small Leak Undetected 2. Low K_{IC} value of weld or base material 3. Excessive mechanical loads 4. Defective Heat Treatment 5. Fatigue	1	4	Weld Repair
		Propagation of Sub-Critical Defects	1. Presence of defects in weld 2. Stress-Corrosion Cracking 3. Underdesign 4. Fatigue	3	3	Weld Repair

Probability Numbers (P)	Definitions
5.4	An off-normal condition which individually may be expected to occur once or more during the plant lifetime
3.2	An off-normal condition which individually is not expected to occur during the plant lifetime however when integrated over all plant components and systems. Event in this category may be expected to occur a number of times
1	An off-normal condition of such extremely low probability that no event in this category is expected to occur during the plant lifetime but which nevertheless represent extreme or limiting cases of failures which are identified as conceivable

Criticality Numbers (C)	Definitions
5	Failure to perform safety function
4	Degradation of safety function
3	No effect on safety but causes unscheduled outage
2	No effect on safety, repair defered until scheduled outage
1	No effect on safety or operation

simplest of tube-to-tubesheet weld: seal pass. In addition a weighting factor must be established to reflect the relative frequency of occurrence of each critical defect size. From a multiplication of these factors for each weld type, one can determine a relative risk of failure (leakage) for the different types of tube-to-tubesheet joints. These risks of failures are summarized in Table 7.

Therefore, if the risk of failure for the tube-to-tubesheet fillet welds is given by R_1 and the risk of failure for some other weld type is R_x, an estimate of the failure rate for this weld type is given by

$$\lambda_x = \left(\frac{R_x}{R_1}\right) \lambda_{1,c} \qquad (9)$$

where $\lambda_{1,c}$ represents the quantitatively obtained value of the fillet weld failure rate at a confidence level C. Therefore, from Eq. (9), the failure rates for the different weld types can be obtained as shown in Table 8.

Table 8. Failure Rates of Different Weld Types

Weld Type	λ_u (year^{-1})	λ_o (year^{-1})
1. Fillet (tube-to-tubesheet)	2.00×10^{-6}	1.07×10^{-7}
2. Fillet (tube-to-boss)	5.92×10^{-7}	3.17×10^{-8}
3. Recessed	9.03×10^{-6}	4.83×10^{-7}
4. Outside Bore Butt	2.33×10^{-6}	1.25×10^{-7}
5. In-Bore Butt	2.30×10^{-6}	1.33×10^{-7}

Therefore, the probabilities of individual tube-to-tubesheet weld failing in one year are given from Eq. (2) by Table 8. The above values represent the condition for a small leak taking place in the weld which could potentially lead to a major sodium water reaction.

Reasons for Ratings in Table 7

All of the types of tube-to-tubesheet welds listed in Table 7 could be used for fabrication with the exception of the seal pass. The seal pass is included in the rating because some testing has been performed at the Tampa Division on this welding pass before the filler pass was added.

Table 7. Relative Risks of Tube-to-Tubesheet Weld Leakage

Type of Weld	Porosity A	Porosity B	Porosity WF	Lack of Fusion A	Lack of Fusion B	Lack of Fusion WF	Cracks A	Cracks B	Cracks WF	Inclusions A	Inclusions B	Inclusions WF	R_f
Seal Pass	4	8	100	2	1	10	2	5	1	1	1	1	3231
Fillet (Tube-to-Tubesheet)	1	7	100	1	1	10	1	5	1	1	1	1	716
Fillet (Tube to Boss)	1	2	100	1	1	10	1	1	1	1	1	1	212
Recessed	4	8	100	2	1	10	2	5	1	1	1	1	3231
Outside Butt Weld	4	2	100	3	1	10	4	1	1	1	1	1	835
In-Bore Butt Weld	4	2	100	2	1	10	4	1	1	1	1	1	825

Cause of Failure: Porosity, Lack of Fusion, Cracks, Inclusions

A - Probability of critical size defect

B - Probability of detecting defect

WF - Weighting Factor

R_f - Risk of Failure

Quantitative Ranking

The relative probability of encountering a critical size defect in the different weld types is established from a scale of 1-10, 10 being the most probable, using the seal pass as reference. Similar numbers are established for the relative probability of detecting the presence of a critical size defect in the different types of tube-to-tubesheet welds. The relative possibility of a weld having one of the different types of defect is established through a weighting factor WF ranging from 1-100, 100 being the most probable.

The following remarks can be made about the defects found in the different types of welds:

1) Porosity

This is the major cause of leaks in tube-to-tubesheet welds and is caused by contamination of the surfaces and/or outgassing of the materials (metals). As noted in Section IV, ii 6, our experience has shown that the number of leaks cause by porosity are affected by the number of passes (fusion pass vs. fusion plus filler pass) and thus the size of the weld (throat measurement). The ratings under the first column reflect these experiences in which the double pass fillet welds have much less chance of forming defect porosity than the other welds.

The second column displays the effect of inspection on the probability of finding defects, and it can be seen that the welds which can be inspected by visual and dye penetrant has a lower possibility of finding a defect than the welds that can be radiographed. The visual and dye penetrant inspections would only detect surface defects. A combination of the two plus a radiographic inspection would detect both surface and internal defects.

2) Lack of Fusion

Experience has shown that this defect is less likely to occur in a two pass weld and more likely to occur in the seal pass and the recessed tube welds. Also, the butt welds lend themselves to this type of defect.

Inspection is equally good for detecting this defect through visual and dye penetrant inspection techniques. An internal dye penetrant and visual inspection technique can be performed on the outside butt weld.

3) Cracks

A crack that would cause a leak is least likely to occur in a two pass weld and more likely to occur in a one pass weld.

The probability of detecting a crack is much greater where visual, dye penetrant and x-ray inspection methods can be used. The probability for an inspection technique to detect a crack in a seal pass, a recessed weld or a fillet weld without x-ray inspection are much less, because the most probable area for a crack to form is the tip of the space between the tube and cladding (or tubesheet). The area is beneath the weld and therefore not normally accessible for visual or dye penetrant inspection.

4) Inclusions

The most likely inclusion that could cause a problem in gas tungsten-arc welding would be a tungsten inclusion from the electrode, and the possibility for this occurring is much less for an automatic system than for a manual system. The possibility and probability for detection is the same for all weld types.

iv) Reliability of Weld Configurations

The possibility of encountering a tube-to-tubesheet weld failing is a function of the individual probability of joint failure and the number of welds in the unit. If p is the probability of failure of a particular tube-to-tubesheet weld type and f the reliability of the joint, the probability of having n failures out of N welds of a given unit is binomially distributed with probability.

$$Pr\{n\} = \frac{N!}{n!\,(N-n)!}\, p^n\, f^{N-n} \qquad (10)$$

However, if p is close to zero so that $f=1-p\simeq 1$ and N is large (≥ 50), the binomial distribution is very closely approximated by the Poisson distribution given by,

$$Pr\{n\} = \frac{Z^n e^{-Z}}{n!} \qquad (11)$$

where $Z=Np$.

Therefore, from Eq. (11), the probability of having at least one leaky joint is given by

$$p_f = 1-e^{-Z} \qquad (12)$$

As given in Table 1, the single tube unit consists of 1778 tube-to-tubesheet welds. Therefore, from Eq. (12) and Table 8, the probability of failure in one year of operation of single wall units with different tube-to-tubesheet weld designs is given in Table 9. Furthermore, it is assumed based on recent tests conducted at W and earlier experiences with feedwater heaters where the tube-to-tubesheet junction was accomplished through a tube expansion into the tubesheet hole, that if the tube is full-depth rolled, the probability of a water-side leak having access to sodium is reduced by 30%. For the conservative estimate it will be assumed that the probability of leak accessibility will not be affected by the rolling process.

Table 9. Probability of Tube-to-Tubesheet Weld Failures of Various Single Wall Units in One Year

	Probability of Failure			
	Tube Rolled		Tube Not Rolled	
Type	Conserv.	Most Likely	Conserv.	Most Likely
Fillet Weld (Tube-to-Tubesheet	.00178	.00013	.00178	.00019
Fillet Weld (Tube to Boss)	.00053	.00004	.00053	.00006
Recessed Weld	.00800	.00060	.00800	.00086
Outside Bore Butt Weld	.00206	.00022	.00206	.00022
In-Bore Butt Weld	.00204	.00021	.00204	.00021

To illustrate the computational procedure that must be followed to generate the probability of failure numbers tabulated in Table 9, consider the most likely estimate of the reliability of the fillet weld (tube-to-tubesheet). From Table 8, $\lambda_o = 1.07 \times 10^{-7}$ year^{-1}. Therefore, the probability of a failure of a fillet weld (tube-to-tubesheet) is obtained from Eq. (2) to be 1.07×10^{-7}. Hence, if the unit consists of 889 tubes, the probability of having at least one failure in a year is given from Eq (12) with N=1778 and $p=1.07 \times 10^{-7}$ as

$$p_f = 1 - e^{-(.00019)} = .00019$$

Similarly, since the single wall plant consists of four loops, two modules/loop, the probabilities of weld failure in one year in a single wall plant, summarized in Table 10 for various joint designs, are obtained from Eq. (12) where N = 8 and the p values given from Table 9.

Table 10. Probability of Tube-to-Tubesheet Weld Failures of Various Single Wall Plants in One Year

Type	Probability of Failure			
	Tube Rolled		Tube Not Rolled	
	Conserv.	Most Likely	Conserv.	Most Likely
Fillet Weld (Tube-to-Tubesheet)	.01414	.00104	.01414	.00152
Fillet Weld (Tube to Boss)	.00423	.00032	.00423	.00048
Recessed Weld	.06200	.00480	.06200	.00685
Outside Bore Butt Weld	.01634	.00176	.01634	.00176
In-Bore Butt Weld	.01618	.00167	.01618	.00167

The probability of failure of a tube-to-tubesheet weld taking place in 30 years of operation of a single wall unit, is given in Table 11.

Table 11. Probability of Tube-to-Tubesheet Weld Failures of Various Single Wall Units in its Design Life

Type	Probability of Failure			
	Tube Rolled		Tube Not Rolled	
	Conserv.	Most Likely	Conserv.	Most Likely
Fillet Weld (Tube-to-Tubesheet)	.05194	.00398	.05194	.00569
Fillet Weld (Tube to Boss)	.01566	.00118	.01566	.00169
Recessed Weld	.21400	.01780	.21400	.02543
Outside Bore Butt Weld	.06025	.00664	.06025	.00664
In-Bore Butt Weld	.05949	.00653	.05949	.00653

Finally, the probability of failure of a tube-to-tubesheet weld taking place in 30 years of operation of a single wall plant, is given in Table 12.

Table 12. Probability of Tube-to-Tubesheet Weld Failures of Various Single Wall Plants in its Design Life

Type	Probability of Failure			
	Tube Rolled		Tube Not Rolled	
	Conserv.	Most Likely	Conserv.	Most Likely
Fillet Weld (Tube-to-Tubesheet)	.3400	.0313	.3400	.0450
Fillet Weld (Tube to Boss)	.1178	.0094	.1178	.0134
Recessed Weld	.8195	.1327	.8195	.1840
Outside Bore Butt Weld	.3825	.0517	.3825	.0517
In-Bore Butt Weld	.3787	.0509	.3787	.0509

To illustrate how the probability values of Tables 11 and 12 are generated, consider once more the fillet weld (tube-to-tubesheet). Since a most likely estimate of the failure rate for this weld type is given in Table 11 as 1.1×10^{-7} year $^{-1}$, the probability of failure in 30 years is given from Eq. (2) as

$$p = 1 - e^{-(1 \times 10^{-7}) \times 30} = 3.2 \times 10^{-6}$$

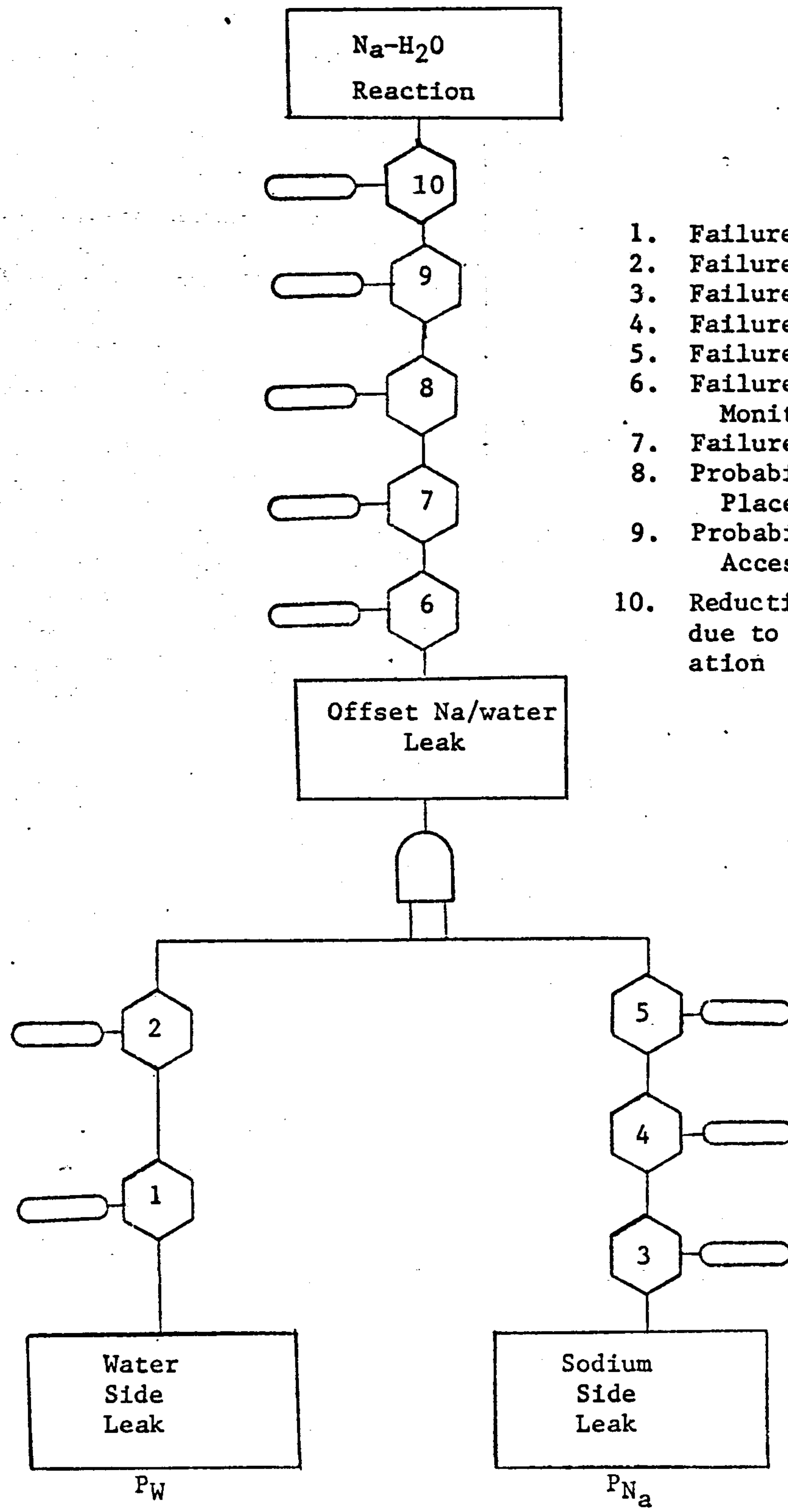
Since the unit consists of 889 tubes, the probability of experiencing at least one failure of this type of weld in the design life of the unit (30 years), Eq. (12) can be employed with N =1778 and p =3.2×10^{-6}. Hence

$$p_f = 1 - e^{-.0057} = .00569$$

Finally, since the plant consists of 8 units, the probability of at least one weld failure in the design life of the plant is given by Eq. (12) with N = 8 and p = .00569. Hence,

$$p_f = 1 - e^{-.0455} = .0450.$$

In order to establish reliability measures of the different duplex tube-to-tubesheet weld configurations consider the following general Fault Tree analysis shown in Fig. 12.



1. Failure to Monitor P_{He} Increase.
2. Failure of Water Vapor Detector.
3. Failure to Monitor P_{He} Decrease.
4. Failure to Detect H_e in N_a.
5. Failure of Sodium Vapor Detector.
6. Failure of Hydrogen Activity Monitor.
7. Failure of Oxygen Activity Monitor.
8. Probability of Water Leak Take Place in Same Tube.
9. Probability of Water Leak Having Access to Sodium Leak.
10. Reduction of probability of failure due to flexibility of weld configur ation

Fig. 12 General Tube-to-Tubesheet Weld Fault Tree

Based on studies carried out at W the following failure probabilities can be assigned to the different leak detection systems.

Table 13. Probability of Failure of Leak Detection Systems

Leak Detection System	Probability of Failure Consv.	Probability of Failure Most Likely
1. Monitor P_{He} Increase	.60	.20
2. Water Vapor Detector	.10	.02
3. Monitor P_{He} Decrease	.90	.50
4. Detect Helium in Sodium	.01	.002
5. Sodium Vapor Detector	.99	.99
6. Hydrogen Activity Monitor	.95	.75
7. Oxygen Activity Monitor	.95	.75

As noted in Table 1, the duplex tube design consists of 793 tubes. Therefore, the probabilities of failures p_W and p_{Na} can be determined for each weld type from application of the Poisson distribution to the values of Table 8. The result of this procedure is shown in Table 14 where for conservatism it has been assumed that $p_{Na} = p_W$ while for a most likely condition $p_{Na} = .1p_W$ to account for the non-corrosive characteristic of liquid sodium.

Table 14. Probability of Failure of Water and Sodium Side Welds For A Duplex Wall Unit In One Year

Weld Type	p_W Consv.	p_W Most Likely	p_{Na} Consv.	p_{Na} Most Likely
1. Fillet Weld (Tube-to-Tubesheet)	.0016	.00017	.0016	.000017
2. Fillet Weld (Tube-to Boss)	.0005	.00005	.0005	.000005
3. Recessed Weld	.0071	.00077	.0071	.000077
4. Outside Bore Butt Weld	.0019	.00020	.0019	.000020
5. In-Bore Butt Weld	.0018	.00019	.0018	.000019

The probability of a sodium and a water side tube-to-tubesheet weld leaks taking place simultaneously in one of the 793 tubes is $(1/793)^2 = 1.59 \times 10^{-6}$. This probability is represented in the fault tree diagram of Fig. 12 by the inhibit gate 8. To account for the effect that the air space between two tubesheets has on the occurrence of a major sodium-water reaction the inhibit gate 9 is introduced in the fault tree diagram.
The intermediate low pressure gaseous space separating double tubesheets in a sodium heated duplex tube steam generator design offers a distinct barrier to the communication of sodium-water reaction products which ultimately could cause a major sodium/water reaction in the tube bundle region. The gaseous space acts to depressurize the steam which may be expelled from a water side tube weld leak and, therefore, drastically counteracts the possibility of forcing this effluent into an available sodium side leak path. Various combinations of water and sodium side weld joints offer differing degrees of retarding this postulated event but the probability of occurrence remains essentially unchanged. Based, therefore, on engineering judgment it is assumed that the most likely probability of combination of events leading to a major sodium-water reaction with a double tubesheet arrangement would be about 10^{-11} whereas a 99% confidence level estimate of this probability would be about 10^{-9}. In addition, it is assumed that since contamination on this region could result from off-set sodium and water side leaks, it is assigned a value of 1.0 to the inhibit gate 8 for double tubesheets weld configurations.

Finally to account for the effect that weld configuration flexibility has on the stress at the weld and hence on the failure probability of the different weld configurations, an inhibit gate 10 is added in the FTA having the values listed in Table 15 following the analysis of Appendix III.

Table 15. Reduction of Probability of Failure Due to Flexibility of Weld Configuration

Weld Configuration	Relative Flexibility
Single Tubesheet/Duplex Tube Not Rolled	1.12
Double Tubesheet/Duplex Tube Rolled	0.15
Double Tubesheet/Duplex Tube Not Rolled	0.15
Single Tubesheet/Duplex Tube Rolled	0.45
Single Tubesheet/Single Tube	1.00

Therefore, the following probabilities of failure can be obtained for the different weld configurations listed in Fig. 10(a)-(f).

Table 16. Probability of Tube-to-Tubesheet Weld Failures of Various Duplex Tube Units in One Year

Weld Configuration		Probability of Failure: Leak Detection		Without Leak Detection	
	Tubesheet	Conserv.	Most Likely	Conserv.	Most Likely
A	Single	5.76×10^{-13}	6.12×10^{-16}	5.76×10^{-13}	6.12×10^{-16}
	Double	5.79×10^{-20}	2.85×10^{-27}	1.20×10^{-16}	1.28×10^{-21}
B	Single	1.80×10^{-13}	1.80×10^{-16}	1.80×10^{-13}	1.80×10^{-16}
	Double	1.81×10^{-20}	8.35×10^{-28}	3.75×10^{-17}	3.75×10^{-22}
C	Single	6.48×10^{-13}	6.84×10^{-16}	6.48×10^{-13}	6.84×10^{-16}
	Double	1.35×10^{-16}	1.43×10^{-21}	1.35×10^{-16}	1.43×10^{-21}
D	Single	9.80×10^{-12}	1.16×10^{-14}	9.80×10^{-12}	1.16×10^{-14}
	Double	2.03×10^{-15}	2.32×10^{-20}	2.03×10^{-15}	2.32×10^{-20}
E	Double	1.81×10^{-20}	8.35×10^{-28}	3.75×10^{-17}	3.75×10^{-22}
F	Single	2.04×10^{-3}	2.10×10^{-4}	2.04×10^{-3}	2.10×10^{-4}

As indicated in Table 1, each duplex tube plant consists of 4 loops, 3 modules/loop. Therefore, from Table 16, the probability of failure of tube-to-tubesheet weld configurations in one duplex tube plant year is summarized in Table 17.

Table 17. Probability of Tube-to-Tubesheet Weld Failure of Different Duplex Tube Plants in One Year

Weld Configuration		Probability of Failure: Leak Detection		Without Leak Detection	
	Tubesheet	Conserv.	Most Likely	Conserv.	Most Likely
A	Single	6.91×10^{-12}	7.34×10^{-15}	6.91×10^{-12}	7.34×10^{-15}
	Double	6.92×10^{-19}	3.42×10^{-26}	1.44×10^{-15}	1.54×10^{-20}
B	Single	2.16×10^{-12}	2.16×10^{-15}	2.16×10^{-12}	2.16×10^{-15}
	Double	2.17×10^{-19}	1.00×10^{-28}	4.50×10^{-16}	4.50×10^{-21}
C	Single	7.78×10^{-12}	8.21×10^{-15}	7.78×10^{-12}	8.21×10^{-15}
	Double	1.62×10^{-15}	1.72×10^{-20}	1.62×10^{-15}	1.72×10^{-20}
D	Single	1.18×10^{-10}	1.39×10^{-13}	1.18×10^{-10}	1.39×10^{-13}
	Double	2.44×10^{-14}	2.78×10^{-19}	2.44×10^{-14}	2.78×10^{-19}
E	Double	2.17×10^{-19}	1.00×10^{-28}	4.50×10^{-16}	4.50×10^{-21}
F	Single	2.45×10^{-2}	2.52×10^{-3}	2.45×10^{-2}	2.52×10^{-3}

Finally the probabilities of failure of the different tube-to-tubesheet weld configurations in 30 years operation of a duplex tube plant are summarized in Table 18.

Table 18. Probability of Tube-to-Tubesheet Weld Failure of Different Duplex Tube Plants During Their Design Life

Weld Configuration		Probability of Failure			
		Leak Detection		Without Leak Detection	
	Tubesheet	Conserv.	Most Likely	Conserv.	Most Likely
A	Single	6.22×10^{-9}	6.61×10^{-12}	6.22×10^{-9}	6.61×10^{-12}
	Double	6.23×10^{-16}	3.08×10^{-25}	1.30×10^{-12}	1.39×10^{-17}
B	Single	1.94×10^{-9}	1.94×10^{-12}	1.94×10^{-9}	1.94×10^{-12}
	Double	1.95×10^{-16}	9.00×10^{-26}	4.05×10^{-13}	4.05×10^{-18}
C	Single	7.00×10^{-9}	7.00×10^{-12}	7.00×10^{-9}	7.00×10^{-12}
	Double	1.46×10^{-12}	1.46×10^{-17}	1.46×10^{-12}	1.46×10^{-17}
D	Single	1.06×10^{-7}	1.25×10^{-10}	1.06×10^{-7}	1.25×10^{-10}
	Double	2.20×10^{-11}	2.50×10^{-16}	2.20×10^{-11}	2.50×10^{-16}
E	Double	1.95×10^{-16}	9.00×10^{-26}	4.05×10^{-13}	4.05×10^{-18}
F	Single	7.35×10^{-1}	7.56×10^{-2}	7.35×10^{-1}	7.56×10^{-2}

V. SUMMARY OF RESULTS

The reliability and safety aspects of different tube-to-tubesheet weld joint configurations have been estimated based on the available operating experience and engineering judgment reflecting differences in the materials of construction, operating temperature, environmental effects, and the impact of fabrication and inspection. Since operating data from LMFBR system components is extremely sparse, it must be emphasized that the estimates are most useful as a means to quantitatively compare designs and only an approximation of the absolute level of reliability of operation availability and safety against a major sodium water reaction. It is recognized that the estimates are to some extent dependent on the specific size of the initial leak. Although the probability of a "large" leak occurring initially is considered remote several possibilities of a major reaction occurring are as follows:

i) The leak could be large due to tube severence from an unanticipated gross overload.

ii) The small leak may result in a large leak as a result of wastage of the leaking tube or an adjacent tube before detection and shutdown can be achieved.

iii) The small leak may be detected when in operation but plugged during shutdown and not be located. The plug results in corrosion of the leaking tube until a large leak results. The above is expected to result in a number of start up and shutdown occurrences not considered in this assessment.

This report considers the effect that different design parameters, such as leak detection capabilities, single vs. double tubesheets and type of weld have on the possibility of various weld configurations to experience a leak as well as a major sodium water reaction.

In reviewing the result of Section IV, the high level of reliability associated with tube-to-tubesheet welds compared to tube reliability[4] is apparent. The reliability increases are in the order $\left\{\frac{P_{f,T}}{P_{f,W}}\right\}_S$ for

for single wall plants and $10^3 \left\{\frac{P_{f,t}}{P_{f,W}}\right\}_D$ or higher for duplex tube plants. Secondly, an extremely large increase can be achieved in the safety against the occurrence of a major sodium-water reaction by double walled tube weld configurations compared to those of single wall weld configurations. Additional increases in tube-to-tubesheet weld reliabilities can be realized by the presence of a second tubesheet and a leak detection system. The reliability levels of weld configurations A through E are of such high magnitude as to reduce the rationale of selecting the most efficient design to be employed in the 1500 MW_e steam generator to economical factors considering cost, availability and safety. There is obviously no reason to specify a tube-to-tubesheet weld design orders of magnitude more reliable than that of the tube.

In regards to the reliability of specific tube-to-tubesheet weld designs, this study indicates that the fillet tube-to-boss weld constitutes the most reliable design. Furthermore, it is expected that additional inspection or testing procedures could significantly increase the reliability of this weld design beyond its already extremely high value. For instance, a helium leak test could be performed after the initial seal pass which is followed by the standard gas leak test upon completion of the filler pass. This procedure will reduce the possible presence of porosity defects which constitute the most common weld defect. In addition, in selecting a weld type one must consider to a large extent the ease of fabrication and prior welding experience which in turn results in high repeatability of quality welds thus re-asserting the basic quality control principle that one does not inspect quality into a manufacturing process. The tube-to-boss fillet weld meets all the requirements of ease of fabrication, and there are many years of experience in producing a very large number of high quality fillet weld for PWR heat exchangers. Furthermore, as noted in Section III (ii), the presence of the machined boss allows for a radiograohic inspection (at a considerable expense) thus greatly improving on the reliability of the PWR fillet weld.

Bibliography

1. Anderson, R. H., Ford, J. A., and Lindsey, P. S., "Design, Fabrication, and Preliminary Operation of the Steam Generators for the Enrico Fermi Atomic Power Plant", APDA-307, August 1968.

2. Koch, L., "EBR-2 plus 10: Is the U.S. Formula Right for Effective LMFBR Development?", Nuclear News, August 1974.

3. Watkins, B., et. al., Paper SM 130/15 in Proceedings of a Symposium on Sodium Cooled Fast Reactor Engineering, IAEA, Monaco, June 1970.

4. Morales, W. J., "Reliability of LMFBR Steam Generator Single Wall and Duplex Tubing", WNET-111, Rev. 1, November 1974.

5. Copeland, J. F. and Licina, G. F., "A Review of 2¼Cr-1Mo Steel for Steam Generator Applications in the Clinch River Breeder Reactor", GEAP-20589, October 1974.

6. Indig, M. E., "Review of Stress Corrosion Cracking Incidents in Nuclear and Fossil-Fired Power Plants", NEDG-1385, June 1972.

7. DeVan, J. H., Hammond, J. P. and Slaughter, G. M., "Materials for LMFBR Steam Generators", Presented at the American Nuclear Society Topical Meeting on Reactors Material Performance, Richland, Washington, April 1972.

8. Hammond, J. P., et. al., "Corrosion of Incoloy-800 and Nickel-Base Alloy Weldments in Steam", Welding Journal 52, 6, 1975.

9. Hoke, J. H. and Eberle, F., "Oxidation of Superheater Materials by High Temperature Steam", ASME Paper 57-A-175, 1957.

10. Thorley, A. W. and Tyzack, C., "The Corrosion Behavior of Iron and Nickel Based Alloys in High Temperature Sodium", Paper SM 85/118 in Proceedings of Symposium on Alkali Metal Coolants, IAEA, Vienna, 1967.

11. Comprelli, F. A., Krankota, J. L., amd Spalaris, C. M., "Performance Limits of Materials for Sodium Heated Steam Generators", International Conference on Sodium Technology and Large Fast Breeder Reactor Design", November 1968.

12. Nuclear Systems Material Handbook, V. 1, Hanford Engineering Development Lab., Richland, Washington, 1974.

13. ASME Boiler and Pressure Vessel Code, Sections III and VIII, 1974.

14. Interpretations of ASME Boiler and Pressure Vessel Code, Code Case 1592, Nuclear Components in Elevated Temperature Service, April 1974.

15. Interpretations of ASME Boiler and Pressure Vessel Code, Code Case 1484-2, Ni-Chr-Fe Tubing (Alloy 600 and 690) at a Specified Minimum Yield Strength of 40.0 ksi Section III, Class 1, 1974.

16. James, L. A., "The Effect of Temperature Upon the Fatigue-Crack Growth Behavior of Two Nickel-Base Alloys, Transactions of the ASME, Journal of Engineering Materials and Technology, October 1973.

17. Brown, W. F., Jr., amd Srawley, J. E., "Commentary on Present Practice", Review of Developments in Plane Strain Fracture Toughness Testing, ASTM STP 463, November 1970.

18. Wessel, E. T., Clark, W. G. and Wilson, W. K., "Engineering Methods for the Design and Selection of Materials Against Fracture", U.S. Army Tank-Automative Center Report AD No. 801005, June 1966.

19. Rubel, P., Reliability Methods in Reactor Technology, ORNL CF 72-3-39, June 1972.

20. Crosetti, P. A., "Fault Tree Analysis with Probability Evaluation, "IEEE Transactions on Nuclear Science, V. 18, 1970.

21. Budney, G. S., "Liquid Metal Heated Steam Generator Operating Experiences", NAA-SR-12534, Liquid Metals Engineering Center, November 1967.

22. "Failure Mode, Effect and Criticality Analysis", Reliability Methods and Procedures (RMP) No. 3-5, Rev. C, Westinghouse Electric Corp., Astronuclear Lab., 1972.

23. Gandadharan, A. C., Gupta, G. D., and Berman, I., "Reliability Evaluation of a Sodium Heated Steam Generator", Reliability Engineering in Pressure Vessels and Piping presented at the Second National Congress on Pressure Vessels and Piping, San Francisco, California.

APPENDIX I

Homogeneous Poisson Process

Consider events (such as a tube-to-tubesheet weld failure) occurring in time on the interval 0 to ∞. Let $N(t_1)$ be the number of events that have occurred from $t=0$ to $t=t_1$. Thus, for any $h>0$, $N(t+h)-N(t)\geq 0$. From this, the following axioms are set to be representative of a homogeneous Poisson process:

Axiom 1 - $N(0) = 0$

Axiom 2 - The process $\{N(t),\ t\geq 0\}$ has independent increments, i.e., the number of failures that will occur in the time interval t_3-t_2 is not influenced by the fact that $N(t_2)-N(t_1)$ occurred in t_2-t_1.

Axiom 3 - For any $t>0$ and $h>0$, $0<P\{N(t+h)-N(t)\}<1$. This means that in any interval (no matter how small) there is a probability greater than zero that an event will occur.

Axiom 4 - $N(t)$ has stationary increments, i.e., constant rate.[23]

Therefore, if a process satisfies the above axioms it is said to be a homogeneous Poisson process for which it is proper to assume a constant failure rate. Thus, it seems reasonable to classify the failure of tube-to-tubesheet welds as a homogeneous process.

Appendix II

Bayesian Statistics

The results of this reliability study contained in Section IV of this report are based primarily on estimates made on the failure rates of different weld designs from known failure experience accumulated through a specified period of time. The assumption of constant failure rate is made in accordance with standard reliability engineering practices. However, it is acknowledged that as more failure data becomes available these initial failure rate estimates might require modification. One well-established approach which is often employed to revise initial estimates of a parameter is the so-called Bayesian approach.

Briefly, it should be pointed out that the basic difference between classical and Bayesian statistics lies in the interpretation of the parameter under investigation. As noted in Section IV, classical statistics treats the parameter (in this case failure rate) as having a single value to be estimated, either by a point estimate or by forming a confidence interval. On the other hand, Bayesian statistics assumes that this parameter has a probability distribution rather than a single value. Thus, since the failure rate of a structural component often varies in time it seems reasonable to treat it as a random variable possessing some known p.d.f. known as the posterior distribution which generates the conditional distribution of the parameter given the values of the observation. Therefore, in Bayesian statistics the information in the sample as summarized by a statistic modifies the statistician's postulated distibution of the parameter.

As example, let λ, the failure rate, be the parameter that one wishes to estimate. One then assumes that λ is a random variable distributed according to the p.d.f. $f(\lambda)$, known as the a priori density function. Given λ, T, an observable variable (in this case, failure time) has a density $g(T)$. If one observes n failures with failure times $T_1, T_2, \ldots, T_n$, the posterior distribution of λ is the well known Bayes' theorem.

$$f(\lambda | T_1, T_2, \ldots, T_n) = \frac{f(\lambda) g(T_1) g(T_2) \ldots . g(T_n)}{\int f(\lambda) g(T_1) \ldots . g(T_n)\ d\lambda} \qquad \text{(a-1)}$$

It can then be proven that the best estimate of λ is given by

$$\lambda^* = \int \lambda f(\lambda | T_1, T_2, \ldots, T_n)\, d\lambda \qquad \text{(A-2)}$$

For practical applications, $f(\lambda)$ is chosen such that Eq. (A-1) reduces to a simple expression. For instance, if T is exponentially distributed with parameter T, it is customary to choose the Gamma distribution as the a priori density.

$$f(\lambda) = \frac{b^{\alpha} e^{-b\lambda} \lambda^{\alpha}}{\Gamma(\alpha)}, \quad \lambda \geq 0 \qquad \text{(A-3)}$$

where α and b are known constants. It can then be shown that the best estimate of λ is given from Eq. (A-2) as

$$\lambda^* = (\alpha + n)/(b + \sum_{i=1}^{n} T_i) \qquad \text{(A-4)}$$

APPENDIX III

Weld Configuration Flexibility and its Effect Upon the Failure Probability of Selected Weld Configurations

A measure the weld configuration failure probability may be achieved by a relative evaluation of the dominate membrane stress, i.e.,

$$\frac{\sigma_{axial}}{\sigma_{axial,\ reference}}.$$

Variation of the above stress components are known to be a function of the given weld configuration flexibility. Relationships relative to this analysis are shown in the following table.

Table 1

Weld Configuration	σ_{axial}
Single Tubesheet/ Duplex Tube	$\frac{L\alpha\Delta T}{A_D\left[\frac{1}{K_T}\right]}$
Double Tubesheet/ Duplex Tube	$\frac{L\alpha\Delta T}{A_D\left[\frac{1}{K_T}+\frac{N}{K_C}\right]}$
Single Tubesheet/ Single Tube	$\frac{P_L}{EA_S^2\left[\frac{1}{K_T}\right]}$ or $\frac{P}{A_S}$

To allow ease in computation the reference weld configuration will be the single tubesheet/duplex tube (not rolled) design, i.e.,

Weld Configuration	$\frac{\sigma_{axial}}{\sigma_{axial,reference}}$
Single Tubesheet/ Duplex Tube (not rolled)	1.0

Continued

3. Single Tubesheet/Single Tube

$$\frac{\sigma_{axial}}{\sigma_{axial,ref}} = \frac{A_D P}{E A_S^2 \alpha \, \Delta T_{ref}} = 0.89$$

A_D = area of inner tube of the duplex tube set = 0.14 in^2

A_S = area of the single tube design = 0.219 in^2

P = 2400 psi

$\Delta T_{ref} = 0.25 \left[T_{NA} - T_{H_2O} \right]$

E = 26.5×10^6 psi

$\alpha = 7.5 \times 10^{-6} \ \frac{in}{in\text{-}^oF}$.

The above constant definition is consistent with the 1500 MW_e hockey stick steam generator description.

Tabulation of the above findings are shown below.

Table 2

Relative Flexibility

Single Tubesheet/ Duplex Tube (not rolled)	1.0*	1.12
Single Tubesheet/ Duplex Tube (rolled)	0.4	0.45
Double Tubesheet/ Duplex Tube (rolled)	0.13	0.15
Double Tubesheet/ Duplex Tube (not rolled)	0.13	0.15
Single Tubesheet/ Single Tube	0.89	1.0*

*Reference Configuration