**An Assessment of Primary
Piping Integrity and Leak
Development Characteristics
for the Clinch River Breeder
Reactor Plant**

March 1976

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Battelle

Pacific Northwest Laboratories

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AN ASSESSMENT OF PRIMARY PIPING INTEGRITY
AND LEAK DEVELOPMENT CHARACTERISTICS FOR
THE CLINCH RIVER BREEDER REACTOR PLANT

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ABSTRACT

An interim assessment is presented of factors affecting primary piping integrity and leak development characteristics in the CRBRP in relation to the "leak-before" break concept. Factors considered here are: the mechanical aspects of crack initiation and growth, sodium corrosion and mass transport, caustic corrosion, fabrication and inspection/surveillance techniques.

An assessment of these factors leads to the following conclusions: while the "leak-before-break" concept appears to have validity, there exist several areas of concern that only further research can resolve:

- the lack of validation of fracture mechanics to highly ductile alloys operating at elevated temperatures under complex stress conditions.
- the lack of understanding of the impact of the various degradation modes of the sodium environment
- the limitations of the proposed inspection/surveillance techniques in localizing piping defections and, then, the extent, cause and potential for the existence of like conditions elsewhere in the piping system.

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1.0 INTRODUCTION

This report is the result of work performed under "Task 4: Pipe Integrity and Leak Development" of the LMFBR Materials Behavior Project sponsored by the Division of Technical Review, Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Commission.

The purpose of this report is to provide an interim assessment of primary piping integrity and leak development characteristics in the CRBRP to assist NRC in its evaluation of the "leak-before-break" concept presented in the CRBRP PSAR. This concept, in essence, states that sodium leak rates will be so low, and leak detection ability so sensitive and comprehensive, that the reactor can be shut down before catastrophic pipe rupture occurs. This report will address those factors affecting the leak development process. While the problem of leak detection will not be discussed in any detail, the importance of the latter problem requires that brief reference be made to it.

Engineering and laboratory studies pertaining to the sodium cooled fast breeder reactor concept have been in progress for several decades. In the U.S., the FFTF and the CRBR plants represent the first large-scale synthesis of proven design techniques, engineering test experience, and theoretical/experimental knowledge evolved from programs within a laboratory climate towards a sodium cooled nuclear plant of near commercial power capacity. A basic proposition being tested by these plants, and their European counterparts, is that the physico-chemical reactivity of sodium is overbalanced by the favorable aspects of its physical property spectrum. The analytical work in defense of this proposition has largely centered on physico-chemical effects of sodium on candidate structural materials,

chiefly the austenitic stainless steels, type 304 and 316. This work has been conducted under both static and dynamic sodium environments that attempt to simulate some of the parameters of the actual working system.

Until fairly recently, there has been relatively little emphasis on the physico-chemical-mechanical property synergism that is a fact of life with every chemically active working fluid, particularly so with liquid metals at thermodynamically acceptable temperatures.

This report will review the criteria and operational parameters that describe the primary piping working environment in the CRBRP and briefly discuss the chemical, mechanical and inspection/surveillance factors having application to piping integrity and leak development. The report will conclude with some identification of problem and confidence areas as they apply to the "leak-before-break" concept.

2.0 PRIMARY PIPING WORKING ENVIRONMENT FOR CRFBR

The CRBRP will incorporate three primary loops, each of which serves one intermediate heat exchanger (IHx) and two steam generators. While the piping details of these three loops differ somewhat, a fairly typical schematic of a primary loop is shown in Figure 1, which presents a rough depiction of the principal bends and loops involved in the circuit. As noted in the figure, the section between the reactor outlet nozzle and the primary pump will be made of 316SS and consists of piping of 36 in. OD with a nominal 0.5 in. wall thickness. The section downstream of the primary pump, up to the reactor inlet nozzle, will be made of 304SS, consisting of piping of 24 in. OD, with a nominal 0.5 in. wall. The primary system, including the IHx, will be housed within the reactor containment building, as shown in Figure 2. It is planned to maintain an atmosphere of nitrogen (plus a small background of an oxidizer, probably

FIGURE 1. Schematic of Typical Primary Loop Indicating Major Bend/Loop Sections in 304 and 316SS Circuits(1)

FIGURE 2. Schematic Plan and Elevation Views of CRBRP Plant⁽²⁾

oxygen), within the containment zone to minimize the structural and hazard consequences of a breach in the sodium containment.

Specifications for the primary piping material, including weld filler material, are given in Tables 1 and 2, respectively. Design, fabrication, construction, erection, testing and inspection standards and codes applicable to the primary piping system are given in Table 3.

TABLE 1. Primary System Piping Materials Specifications⁽³⁾

<u>Component</u>	<u>Product Form</u>	<u>ASME Specification No.</u>	<u>Standard</u>	<u>Grade</u>
36 in. diam piping (hot leg)	welded pipe	SA-358	M3-7T	316*
36 in. diam elbows (hot leg)	welded fittings	SA-403	M2-5T	WP316*
24 in. diam piping (hot leg)	welded pipe	SA-358	M3-7T	316*
24 in. diam elbows (hot leg)	welded fittings	SA-403	M2-5T	WP316*
24 in. diam piping (cold leg)	welded pipe	SA-358	M3-7T	304
24 in. diam elbows (cold leg)	welded fittings	SA-403	M2-5T	WP304
2 in. diam piping (IHX Vent)	seamless pipe	SA-312	M3-6T	316H
2 in. diam elbows (IHX Vent)	seamless fittings	SA-403	M2-5T	WP316H

*Carbon Content 0.055 to 0.085 percent.

Various steady-state and transient specifications for the CRBRP system which affect the primary piping working environment and conditions are given in Table 4 and Figure 3, Table 5 and Figure 4, respectively.

Apart from the physical, mechanical and chemical conditions imposed by the transport of the primary sodium between the reactor and the IHX, the working environment of the primary piping system will include the thermal insulation blanket and the ambient atmosphere in the containment building.

TABLE 2. Primary Heat Transport System Component
Weld Filler Materials Specifications⁽⁴⁾

<u>Weld Material Form</u>	<u>RTD Standards</u>	<u>Filler Material Classification</u>
Stainless Steel	M1-1	E 308L-15 or 16
Covered Electrodes		E 308-15 or 16 E 316L-15 or 16 E 316-15 or 16 E 16 - 8 - 2
Stainless Steel	M1-2	ER 308, ER 308L
Bare Rods and Electrodes		ER 316, ER 316L ER 16 - 8 - 2

Appropriate weld rod materials for guard vessels will be identified when the guard vessel material is selected.

TABLE 3. Design, Fabrication, Construction, Erection, Testing
and Inspection Standards for Various Primary Loop
Components⁽⁵⁾

<u>Component</u>	<u>Applicable Standard and Class</u>
PHTS Pump	ASME III, Class 1
IHX	ASME III, Class 1
Check Valve	ASME III, Class 1
Piping	ASME III, Class 1
Flowmeter	ASME III, Class 1
Thermowell	ASME III, Class 1
Pressure Taps	ASME III, Class 1

Class 1 nuclear component analysis shall be in accordance with following rules:

- 1974 Edition ASME Boiler and Pressure Vessel Code; addenda through and including Summer 1974, Section III.
- ASME Code Case 1592, "Class 1 Nuclear Components in Elevated Temperature Service"
- RDT E15-2T (Supplement to Section III)
- RDT F9-4T (Supplement to Code Case 1592)
- Code Case 1593 (fabrication and installation); Code Case 1594 for inspection; Code Case 1595 for testing; Code Case 1596 for overpressure protection.

TABLE 4. Miscellaneous Specifications for CRBRP System
Affecting Primary Piping

<u>Specification</u>	<u>Value/Reference</u>
<u>Power:</u>	
nominal 100% power (MWt)	975 (Reference 6)
overpower limit (MWt)	1121
operating range (% rated power)	40-100
maximum operational step load change (% RP)	+/- 10
maximum operational ramp load change (\$ RP/min)	+/- 3
<u>Primary piping T and P spectrum for various conditions:</u>	see Figure 3
<u>Sodium:</u>	
primary sodium flow rate (lb/hr)	41.5-44.5 x 10 ⁶
maximum sodium velocity in nonreplaceable components (ft/sec)	30
oxygen limits (ppm)	≤2 (T > 800F) (Reference 7) ≤5 (T < 800F)
<u>Containment bldg. atmosphere:</u>	N ₂ (plus 1 +/- 0.02 vol% (Reference 8)
<u>Design life nonreplaceable components (yrs):</u>	30 (Reference 6)
<u>Thermal insulation chemically compatible with piping:</u>	Reference 9
<u>Piping support system adequate for conceivable thermal, mechanical and seismic conditions imposed on piping:</u>	Reference 10
<u>Leak detection system adequate for comprehensive monitoring for breaches in primary sodium containment envelope:</u>	Reference 11

Under minimal water (vapor/liquid) incursion to the primary zone, and minimal sodium spill/leak incidence, the thermal insulation is not expected to perturb the structural quality of the primary piping significantly. Water presence and/or extensive sodium leaks can aggravate the piping-insulation compatibility problem and add substantially to the burden of plant maintenance.⁽⁹⁾ Under the design specification for the containment atmosphere (N₂ plus 1 vol% O₂), a sodium leak/spill event is not expected to result in unmanageable sodium chemical reaction. Depending on the local environment attending the leak/spill (degree of confinement, temperature, structural details, residence time of sodium, etc.) sodium does, however,

Section	Condition				
	Refueling	Hot Standby	40% Power (390 MWt)	80% Power (780 MWt)	100% Power (1121 MWt)
A	400°F/6.8 psig	600°F/6.6 psig	910°F/6.1 psig	974°F/5.4 psig	1015°F/4.9 psig
B	400/9.1	600/8.9	910/8.2	974/6.9	1015/6.0
C	400/14.4	600/14.3	910/34	974/115	1015/168
D	400/6.5	600/6.4	910/26	974/104	1015/155
E	400/1.3	600/1.4	610/19	674/88	715/133
F	400/18.5	600/18.1	610/33	674/95	715/134

FIGURE 3. Steady-State Operating T/P Values at Various Points of Primary Piping System for Various Conditions(12)

have some potential for forming corrosion aggressive species with amounts of water vapor and oxygen which could be acceptable under current atmosphere specifications.⁽⁹⁾ Larger concentrations of water/oxygen due to various conceivable deviations from the operating plan, can greatly enlarge the structural damage and hazard spectrum attending a sodium leak/spill event. (Further discussion in Section 3.3.)

The primary piping working environment is, thus, comprised of the stress, temperature and time factors derived from the function of containment and transport of the primary sodium; the physico-chemical factors relating to the action of sodium (and sodium contaminants) on the piping internal surface; and the physico-chemical factors relating to the interaction between the piping outer surface and the external environment, with, and without, inadvertent sodium intervention. Such an environment patently

TABLE 5. Various Transient Event Frequencies and Criteria
Imposed on Primary Piping System⁽¹³⁾

Normal Events:

Event	Frequency/30 yr
• dry system heatup and cooldown	5 total system, plus 8 per loop
• startup from refueling T	120
• startup from hot standby T	630
• shutdown to refueling T	60
• shutdown to hot standby T	210
• loading and unloading	9300 (each)
• load fluctuations	4600 (each, up and down)
• step load changes of +/- 10% full load	750 (each)
• steady state T fluctuations	30×10^6
• steady state flow induced vibrations	1×10^{10}

Upset Events:

• reactor trip from full power	180
• uncontrolled rod insertion	10
• uncontrolled rod withdrawal from 90% power	10
• uncontrolled rod withdrawal from startup	10
• partial loss primary pump	2 per loop
• loss of power to primary pump	5 per loop
• primary pump pony motor failure	5 per pump

Emergency Events:

• primary pump mechanical failure	(each component must sustain 5 occurrences of most severe tran- sient for that component (one for every 6 yr) and two consecutive occur- rences of most severe event)
• loss of primary pump pony motor with failure of check valve to shut	
• inadvertent dump of intermediate loop sodium	
• etc.	

(note: more complete list of normal, upset and emergency events
given in Reference 13)

hot leg
reactor to pump

hot leg
pump to IHX

cold leg
IHX to reactor

FIGURE 4. Third Level Design Loading Requirements⁽¹⁴⁾

affords a prime challenge to design, fabrication/installation, inspection/surveillance and operation/maintenance abilities if the envelope of primary piping system performance is to be held within generally safe, and economic, bounds.

3.0 ASSESSMENT OF FACTORS AFFECTING PIPING INTEGRITY

3.1 MECHANICAL ASPECTS OF CRACK INITIATION AND GROWTH

Failure of the sodium containment provided by the primary piping of the LFMBR can occur, to some degree, from many causes. While sudden failure, a pipe break, due to a single overload is regarded as highly improbable in view of current design sophistication and conservatism, there is some probability of leaks resulting from through-wall penetration of piping defects.

Small flaws, or cracks, are always present in the pipe wall. Fabrication, handling and installation can each produce this type of damage. It may be argued that, due to the very high quality standards being applied to reactor coolant circuits, the probability of undetected defects remaining in the pipe wall is extremely low. Nevertheless, for safety reasons, the presence of small initial cracks has to be assumed. These small cracks can grow under cyclic loads (fatigue), thermal stresses (thermal fatigue), aggressive environment (corrosion fatigue and stress corrosion), or a combination of all these factors. The direction of crack growth in pipes can usually be predicted: a crack in the pipe wall will tend to propagate perpendicularly to the main stress axis. Thus, a crack will tend to advance through the wall thickness faster than it will elongate in the longitudinal, or circumferential, direction. Once having extended through the wall, a through-the-wall crack produces either a leak or a rupture, depending on whether, or not, the crack has reached a critical length. The critical crack length can be calculated from fracture mechanics theory, and depends on the pipe geometry (radius and thickness of pipe) and the stress level. If a sub-critical crack penetrates the wall and produces a leak, and if this leak is not detected, the crack may grow longitudinally and cause the pipe to fail by bulging.

The toughness of 304 and 316 stainless steel is so great that large yield zones will develop at both ends of the crack in the longitudinal direction. This yielding inhibits further crack growth and tends to force the through-crack to bulge outward, producing a large opening.⁽¹⁵⁻¹⁷⁾ Therefore, in lieu of major internal degradation from environmental factors, leaks would be expected to occur in stainless steel pipes prior to pipe rupture.

There are a number of areas of concern that require further investigation, however. These are:

- possible reductions in stainless steel ductility due to long-term creep exposure which could reduce toughness and enhance crack growth rates
- metallurgical transformations due to sodium action (such as carbon depletion) and long exposures at sensitizing temperatures which could affect grain boundary response to sodium and, hence, crack development and propagation characteristics under service stresses
- effects of high cycle fatigue on crack formation; high cycle fatigue will produce cracks if loads are above the endurance limit; no tests have been conducted out to 10^{10} cycles; corrosion can markedly affect the endurance limit
- effects of corrosion on crack growth rates; corrosion is a time dependent process and, as such, subject to many variables; crack growth rates cannot be reliably predicted under a potentially corrosive environment; the chemistry of corrosive agents in the vicinity of the crack is very complex and can change during the course of the crack growth.
- the effects of thermal shock on structural behavior; thermal shocking produces a low cycle fatigue and it can occur in areas of mixing of sodium streams of different temperatures, mainly at piping junctions
- the limitations of fracture mechanics in dealing with crack growth in high ductility materials, operating at elevated temperatures under complex stress histories (i.e., creep-fatigue loading under nonaxisymmetric conditions).

In summary, the leak-before-break concept appears supportable for the primary piping circuit, with some reservations that are concerned with potential degradation factors inherent in the reactor environment, and with the analytical tools presently available. The favorable aspects relate to: the small size of defects left undetected during fabrication and installation as a result of the quality assurance program; the inherent high toughness of the stainless steel piping material. The areas of concern relate to: potential structural degradation by creep-fatigue interaction, thermal

shock, high cycle fatigue of long duration, and, particularly, sodium corrosion and mass transfer effects on crack growth rates and endurance limits; the present limitations of the fracture analysis discipline in dealing with ductile materials under a high temperature, chemically active environment.

3.2 SODIUM CORROSION AND MASS TRANSFER

Sodium influence on structural materials is a complex function of the current metallurgical state of the material, the local temperature, the local sodium hydrodynamics (flow rate, turbulence, etc.) and the dissolved and particulate species in the sodium that may have physical and/or chemical influence on the sodium-metal interaction. Furthermore, the corrosion response of all the materials in a given loop affect the sodium impurity background at a given point; and the local sodium action may change drastically with respect to axial distance, due to this local background, even under sensibly isothermal conditions. Sodium action may be described by the "uniform" loss of metal (mils/yr); or it may be described by detailing the concentration and identity profiles within the metal of the various substitutional (Cr, Ni, Mn, etc.) and interstitial (C, O, N, B) elements and the various solid solutions, compounds and phases involving these elements. At a given time, these profiles represent the local net result of the removal and deposition of these elements throughout the circuit. While high temperature tends to favor removal of elements to the sodium, temperature is only one of a complex of factors that influences the removal/deposition of the various species and their compounds. This is indicated in Table 6. Oxygen in sodium has a strong influence on mass transfer, and high oxygen concentration increases both the uniform metal attrition rate and the selective leaching of various elements.

For the purpose of estimating wall thickness loss as a function of the local temperature, sodium velocity and oxygen content, Westinghouse⁽¹⁹⁾ performed a statistical analysis of the least ambiguous data from various sources and developed the following relationships for the velocity sensitive (<10 ft/sec) and insensitive (>10 ft/sec) regimes:

TABLE 6. Factors Affecting Mass Transfer in Sodium⁽¹⁸⁾

	Physical	Chemical
Source	Area exposed to sodium Temperature Metallurgical condition Diffusion of components Heat flux	Composition of source material Kinetics of precipitate dissolution Formation of surface layers
Sodium	Fluid dynamics: flow rate and turbulence Diffusion of reactants and/or products through solid/liquid interface boundary layer Presence of particulates	Impurity species present for interaction Kinetics of solution Saturation solubility of components and/or their carriers Kinetics of decomposition of carrier species
Sink	Area exposed to sodium Temperature profiles Diffusion of components Heat flux	Composition of sink material Nucleation of precipitates Growth of precipitates Formation of surface layers

$$R/\phi = 6.69 \times 10^7 \exp(-18120/T), \text{ for } V > 10 \text{ ft/sec}$$

$$R/\phi = (1.17 \times 10^7 + 3.50 \times 10^6 \times V) \exp(-18120/T), \text{ for } V < 10 \text{ ft/sec};$$

where R is the linear corrosion rate (mils/yr), ϕ is the oxygen concentration (ppm) determined by the vanadium wire equilibration technique, T is °K, and V is velocity in ft/sec. These relationships are applicable to both 304 and 316SS, and are cited in the PSAR.⁽²⁰⁾ Using specified oxygen limits appropriate to the temperature⁽⁷⁾ (≤ 2 ppm for T > 800°F, ≤ 5 ppm for T < 800°F), the linear thickness loss rates for 1015 and 715°F are 3.30×10^{-2} and 2.85×10^{-4} mils/yr, respectively (see Figure 3), amounting to thickness changes of approximately 1 mil and 0.01 mil, respectively, for a 30 year life. These relationships represent the most quantitative assessment of sodium corrosive action to date; yet, they reveal nothing of the structural effects of sodium beyond simple dimensional change.

Some of the complexity of the micro-details associated with sodium selective leaching of various elements is shown in Figure 5. Removal of austenite stabilizers (e.g., Ni, Mn, C, N) can cause the metastable austenite to change to ferrite under appropriate temperature/strain conditions. Figure 6 suggests the relative magnitude of the ferrite and uniform corrosion penetrations as a function of exposure time for austenitic stainless steel at 550°C. The austenite-ferrite conversion starts at grain boundaries and eventually consumes the grain, resulting in a ferrite layer on the outer surface and a gradient of ferrite penetration along the grain boundaries of the interior metal.⁽²²⁾ An added potential structural complication with 316SS is the possibility of formation of the Fe-Cr sigma phase under the aggregate influence of temperature, time and strain conditions that could obtain in the 316SS sections of the primary loop. Sigma is believed to

FIGURE 5. Element Concentration Profiles in Types 304 and 316 Stainless Steel Upon Exposure to Flowing Sodium⁽²¹⁾

FIGURE 6. Uniform Corrosion and Ferrite Penetrations in Austenitic Stainless Steel Versus Exposure Time at 550°C⁽²²⁾

nucleate at the ferrite-austenite boundaries and grows at the expense of the ferrite.⁽²³⁾ The mechanical influence of sigma is a function of its quantity and morphology. Its brittleness can be detrimental to ductility and possibly a source of cracks under creep-fatigue excitation. Although sigma formation has generally been ascribed to temperatures in excess of 1000°F, the lower limit of its formation range is apparently lowered by an increase in time at temperature.⁽²⁴⁾ The metastability of the austenitic stainless steel structure of 304 and 316SS is also manifested by the well known carbide precipitation (sensitization) phenomenon, which occurs in the temperature range of 900 to 1600°F. The average operating temperature of the primary loop hot leg will be well within this range (Figure 3), resulting in solid solution alloy depletion in the neighborhood of grain boundaries; chromium is the principal element affected and reduced corrosion-resistance is the result. Other phase modifications near the surface of the containment materials are possible. These depend upon the strength of various elemental

and compound sources available for pickup by the sodium and the receptivity of the metal surface for transported species that can be incorporated in the structure in solid solution or as new phases. Carbon, for example, is of special importance in circuits with a high carbon potential (e.g., secondary sodium circuit), and carbon deposition has resulted in severe embrittlement of the austenitic stainless steels.⁽²⁵⁾

The interstitial elements C, N, B and O are known to significantly influence the strength and ductility of metals. Commercial 304 and 316SS will contain all of these elements, whose amount and distribution will be affected by the various factors of sodium exposure noted previously. Most of the studies of sodium action on these interstitials have ignored, or not regarded, the strain factor as a prime variable, although the influence of plastic strain on transport of interstitials is now recognized, if not well understood. Under the service stress/temperature field, the current bulk concentration of these elements will be of less importance than will be their concentration gradients and the resultant local mechanical property influence of the gradients. These interstitial elements may also provide the mechanism for penetration of sodium into the metal structure, principally along grain boundaries, via physico-chemical reaction of sodium with the elements or with their compounds.⁽²⁶⁾

Both substantial composition and phase modification will, therefore, occur in the near surface layer of the 304 and 316SS components of the primary loop. The stability of these structural gradients under long-term exposure to the sodium working environment, characterized by variable temperature, stress and sodium impurity background, is not well known. The crucial factor of the mechanical property effects of these structural changes, as a function of service life, is a major problem of sodium technology that has not been addressed substantially until fairly recently. This statement applies most particularly to circuit zones where local strain accumulation may develop under the impetus of creep/fatigue and constraint factors. Generalizations (e.g., imputing virtually high purity inert gas, high vacuum, characteristics to sodium with respect to fatigue and corrosion-fatigue action)⁽²⁷⁾ based on extremely limited test experience are very difficult to support. In the

case of creep-fatigue, it would be imprudent to ignore the well-established potential of "working" quality sodium for altering the chemical and physical characteristics of the near-surface layers which can be crucial to creep-fatigue response.

The chemical homogeneity and low carbon potential represented by the materials comprising the primary loop (316, 304SS) is a favorable factor when considering deterioration of structural quality by mass transfer of substitutional and interstitial elements. The status of knowledge concerning the environmental factors noted above, however, encourages some qualification of long-term predictions of structural stability.

3.3 CAUSTIC (NaOH) CORROSION

In addition to the chemical and physical effects associated with metallic sodium, the use of sodium as a coolant will involve various products of the reaction between sodium and the components of the external atmosphere, principally water vapor and oxygen. Of these products, NaOH is the most important from the standpoint of incidence probability and general corrosion aggressiveness. Caustic (NaOH) may intrude the operating plan of a LMFBF plant in several ways:

- during reconditioning of veteran sodium system components by reaction of residual sodium with water vapor (see Reference 9)
- reaction of leak/spill sodium with ambient water vapor
- vestigial NaOH introduced to the working system by improperly cleaned components.

The sodium-water reaction can produce NaOH over a range of H_2O partial pressures and temperatures that probably includes conceivable conditions attending primary system spill/leak events.⁽⁹⁾ The austenitic stainless steels exhibit a sensitivity to caustic attack over a wide range of the NaOH concentration-temperature field, as indicated in Figure 7. Caustic action increases with temperature and with repeated exposure of the metal to caustic, in addition to the obvious factor of caustic residence time on the affected material. The problem of leak detection and correction is

FIGURE 7. Corrosion Data for Austenitic Stainless Steels in NaOH(28)

complicated by the thermal insulation on the primary piping. Furthermore, insulation might be expected to increase the temperature attendant to a leak event that is fed by both process and chemical reaction heat.

While "uniform" corrosion attack from caustic exposure is not expected to be troublesome, given reasonable attention to leak/spill events, the intergranular penetration spikes that are possible at sensitized zones of the 316/304 stainless steel circuit cannot be so qualified, particularly where there has been some plastic strain accumulation. Caustic attack from the external surface could seriously perturb corrosion predictions based solely on the internal, metallic sodium, environment. There is, therefore, ample incentive for good surveillance and housekeeping when one considers the caustic corrosion potential of spill/leak incidents.

3.4 FABRICATION FACTORS

The overall fabrication technology associated with stainless steel in primary nuclear plant service has benefited from many years of broad-scope research and development. This is now manifested in the various codes and standards affecting as-fabricated quality of stainless steel components for nuclear plants. While the welding process has been the recipient of much of this attention, it remains a prime study area and a principal concern in LMFBR stainless steel fabrication. The nature of the weld process is such that depending on the specifics of the weld zone, the type of filler material, the welding parameters and the post-weld heat treatment, the weld represents a very substantial perturbation to the circuit, in terms of gross chemistry and a myriad of macro- and micro-structural details, including residual defects. Accordingly, the welding operation is exceedingly difficult to standardize and, therefore, to qualify for a rigorous service environment. Specifically, the present concept of developing some ferrite in the weld zone to minimize hot cracking⁽²⁹⁾ increases the possibility of sigma phase formation at the higher temperatures of the primary circuit. The corrosion effects, and mechanical property implications, of various sigma quantities and morphologies is not known to any extent for the primary sodium environment. Furthermore, even without corrosion intervention, considerable work is in progress to bring the general mechanical property spectrum of the weld-affected zone into acceptable consonance with that of the 304 and 316 stainless steel parent material.⁽³⁰⁾ The present area of uncertainty pertinent to the weld zone is considerably larger than for the parent 304 and 316 material of the primary circuit. Accordingly, the weld zones should receive first priority in the pre-service and on-line inspection and surveillance program.

3.5 INSPECTION/SURVEILLANCE PROCEDURES

Preoperational and Acceptance Inspection Criteria

The design, construction, erection, testing and inspection standards for LMFBR primary piping loop have been established to meet the stringent requirements developed under ASME Section III, Class I, RDT 15-2T,

RDT F9-4T and other designated code case documents. The testing and inspection phases will be an integral part of establishing the preoperational integrity and acceptance criteria of the primary piping. The weld area, which is one of the most critical areas, will be volumetrically examined utilizing radiographic procedures as the principal test method.

Recent developmental research in acoustic emission (AE)^(31,32,33) indicates that weld defects caused during the welding process can be detected and qualitatively classified by AE technology. Weld defects, such as cracks, which were not detectable by radiographic processes because of the defect orientation, were detected with specifically designed AE instrumentation.⁽³²⁾ Since integrity of the welds is of paramount importance, consideration should be given to further research in acoustic emission monitoring of type 304 and 316 stainless steel to determine the applicability of the techniques for the seam and girth welds of the piping. Where practical the AE-technology might supplement present code inspection requirements (ASME/RDT) to maximize the weld quality in the primary piping.

Inservice Inspection Criteria

Inservice inspection programs are still being developed under ASME Section XI, Division 3 (draft five currently being developed by committee). It is expected that the inservice inspection/surveillance systems include the guard vessel protection/surveillance system, sodium leak detection system, and visual examination of the piping. The principal means for localizing sodium leaks, once detected by the leak detection system, is through visual examination (e.g., remote TV cameras) utilizing accesses designed to permit viewing the primary coolant boundaries of the PHTS cells and pipeways. Thermal insulation must be regarded as an impediment to accurate visual localization of the leak source. Periodic ultrasonic volumetric inspection of select sections of the primary loop may be utilized toward the objective of leak anticipation and prevention (procedure not yet established).

The finalized procedures accepted by ASME Section XI, Division 3 committee should provide maximum system safety and protection. However, from

an operational standpoint the integrity of the primary piping remains a concern. While the inspection systems proposed will undoubtedly detect the presence of a sodium leak, the detection of a single leak casts question of the origin of the defect that caused the leak. Questions which pertain to the extent of the cracking in the zone of the leak or the potential of like material condition in other sections of the loop or in like locations of other loops will require in-depth analysis which must include volumetric nondestructive examination or integrity monitoring of suspect areas. Visual techniques proposed are limited to surface conditions and, therefore, must rely on presence of a through-wall crack that produces a leak.⁽¹⁵⁾

Even though alternate NDE test methods may not be required to provide operational safety, they must be developed to a level where they can be adapted to verify the structural integrity and aid in the analysis of the mechanism leading to development of cracks which cause sodium leaks.

There are three nondestructive test methods that have potential for being adaptable to various phases of the temperature and radiation environment in the primary loop. These include ultrasonics, acoustic emission and electro-thermal.⁽³⁴⁾ Of these only acoustic emission has the potential for monitoring integrity in an on-line operational condition (e.g., 1000°F).

Ultrasonic examination at elevated temperatures (400 to 600°F) have been made but the techniques are not developed for remote examinations such as exist in the piping loops.

Acoustic emission monitoring at temperatures as high as 650°F in zircalloy tubing has demonstrated that crack growth can be detected and growth rate could be predicted.⁽³⁵⁾ Work with 304 stainless steel at temperatures of 550°F has demonstrated that stress corrosion cracking can be detected. However, the application of the technology to the monitoring of integrity or crack growth in LMFBR piping is not established.

The electro-thermal technique⁽³⁴⁾ shows potential for imaging flaw size with infrared techniques, however, the development is in a "proof of principle" status and requires further research.

While the potential for these methods exists, the technology has not been extended to a level where they can be utilized or adapted for periodic or continuous inservice inspection of LMFBR piping. Further research addressed to advancing the technology is required and a determination of the extent to which these test methods may be applied is essential.⁽³⁶⁾

To assure the maximum quality of the piping used in the primary loop, the inspection procedures established under ASME Section III may be beneficially supplemented by the addition of acoustic emission monitoring during the welding process used for both the seam and girth welds. Further research is required to develop the technique for materials used for the primary piping loop. Inservice inspection techniques proposed in the CRBRP PSAR are to be based on ASME Section XI, Division 3 and should provide the safety and reliability requirements for the piping system. However, it must be assumed that cracks will occur and that leaks will develop. Of concern, here, is that once a crack penetrates the pipe and a leak occurs, the analysis of the extent, cause and potential for existence of like conditions in other sections of the piping system must be addressed and the ability of the proposed techniques for analysis of this scope is questionable. Nondestructive examination methods can support this analysis and provide data that can determine if a generic or isolated condition exists. However, to utilize the basic technology available, further research in applicable nondestructive test methods is required to develop tests that can be utilized at the required time.

4.0 SUMMARY AND CONCLUSIONS

Defection of the sodium containment provided by the primary piping of the LMFBFR can occur, to some degree, from many causes. While sudden, massive failure, a pipe break due to a single overload is regarded as highly improbable in view of current design sophistication and conservatism, there is some probability of leaks of various extent, which signal through-wall penetration of piping defects.

Small flaws, or cracks, are always present in the pipe wall and weld zones. Fabrication, handling and installation can each produce this type of damage. It may be argued that, due to the very high quality standards being applied to reactor coolant circuits, the probability of undetected defects remaining in the pipe wall is extremely low. Nevertheless, for safety reasons, the presence of small initial cracks has to be assumed. Depending on size, location, stress fluctuations caused by operational cycles, vibration and thermal transients and aggravation by corrosion, initial small cracks can grow. The direction of crack growth can usually be predicted. Surface cracks inside the pipe wall will tend to enlarge perpendicularly to the main stress direction. Accordingly, a crack will tend to propagate in a radial direction (through the pipe wall) faster than it will elongate in the circumferential, or longitudinal, direction.

Crack initiation and evolution may be affected by sodium in a number of ways, including:

- selective leaching of an intergranular concentration of a metal-interstitial compound (e.g., carbide, oxide, nitride) caused by long residence in the sensitizing temperature range
- selective leaching of substitutional and interstitial elements leading to austenite-ferrite conversion and eventually some presence of the brittle sigma phase
- lowering of free surface energy and/or metal-metal bond strength by sodium atom adsorption (liquid metal embrittlement phenomenon)

- mass transportation and deposition of chemical species and compounds which promote the formation of brittle phases, or embrittle existing phases (carbon, and carbon compounds are a prime example).

The existing fracture mechanics discipline has virtually no capacity to deal with chemically-assisted structural degradation processes such as the above. Furthermore, it appears to be severely limited in purely mechanical analysis in dealing with the plastic deformation which can be associated with crack evolution in materials having the high ductility represented by the austenitic stainless steels. The latter difficulty is compounded by an increase in service stress history complexity (i.e., creep-fatigue loading under nonaxisymmetric conditions).

Estimations of unstable crack size for austenitic stainless steel components comparable to CRBRP primary hot leg piping have strongly supported the leak-before-break philosophy^(15,37) and appear to allow a very substantial margin for error in accounting for sodium effects. However, most authorities on fracture mechanics predictions having some cognizance of potential sodium physico-chemical effects qualify the cracking predictions by recognizing the need for better information on sodium structural effects.

Some of the important areas of concern with regard to sodium effects are:

- the long-term effect of sodium selective dissolution of the substitutional and interstitial elements of the 304 and 316 stainless steels on mechanical properties is not well known and the ability of NDT techniques to analyze structural change resulting from sodium action is very limited; there is, therefore, strong motivation for design provision for periodic removal and comprehensive metallurgical examination of primary piping sections deemed most vulnerable to sodium attack under the impetus of service stresses and temperatures;
- the use of bulk concentrations of substitutional and interstitial elements in estimating sodium mechanical property effects is an oversimplification; it does not give proper emphasis to changes in the surface layer that could drastically affect the response to creep-fatigue stressing at elevated temperatures;

- the applicable design codes give only qualitative recognition to corrosion/mass transfer influence on mechanical properties; the ability of current structural analysis techniques to deal with corrosion-stress (strain) synergism is very limited, particularly for the most critical structural zones where there may be local strain accumulation as a result of service and constraint conditions;
- the possibilities for microstructural modifications that could be inimical to long-term serviceability are relatively extensive at weld zones where there is less opportunity for control of composition and structural details affecting mechanical properties; the ferrite-sigma transition is of particular concern at primary piping service temperatures; the influence of sigma quantity and morphology on structural quality under complex stress/temperature conditions is not known to any extent; thus, weld zones should be a prime subject for the inspection program noted above;
- the upper range of the primary piping service temperature falls well within the 800 to 1600°F sensitization temperature range for austenitic stainless; the grain boundary carbide network resulting from this precipitation phenomenon will become more extensive with service time and is also affected to some extent by stress/strain history; the implications of this characteristic of 304 and 316 stainless steel with respect to sodium physico-chemical action on the structure are virtually unknown for service times in excess of approximately 10 years.
- the potential for serious structural damage from caustic (NaOH) associated with sodium spill/leak events is incentive for the best possible leak detection and correction regimen;
- in terms of pipe inspection and surveillance, the ability to localize a leak and to analyze the extent, cause, and potential for existence of like conditions in other sections of the piping system is not available with the proposed techniques; considerable technology for this task is available, but further research is required before it can become of comprehensive practical assistance to the CRBRP.

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