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RECOMMENDED TEST PROGRAM TO DETERMINE
CRACK GROWTH RATE IN DOUBLE-SHELL TANK MATERIALS

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CONTENTS

	<u>Page</u>
1.0 BACKGROUND.	1
2.0 CRACK GROWTH RATES.	1
2.1 GENERAL CONSIDERATIONS	1
2.2 EXISTING DATA ON MILD STEELS	2
3.0 RECOMMENDED TEST PROGRAM.	2
3.1 TEST METHOD.	2
3.2 MATERIALS.	4
3.3 SPECIMENS.	5
3.4 ENVIRONMENTAL CONDITIONS	5
3.5 TEST PROCEDURES.	6
3.6 TEST PRIORITIES.	6
4.0 COST AND SCHEDULE	7
4.1 COST ESTIMATE.	7
4.2 SCHEDULE ESTIMATE.	7
5.0 REFERENCES.	9

TABLES

Table 1. Test Program	8
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RECOMMENDED TEST PROGRAM TO DETERMINE CRACK GROWTH RATE IN DOUBLE-SHELL TANK MATERIALS

1.0 BACKGROUND

Westinghouse Hanford Company (WHC) is planning to perform ultrasonic examination (UT) of the tank wall in double-shell tanks (DSTs) (Pfluger 1994). A major objective of these examinations is to determine whether various corrosion processes, including stress corrosion cracking (SCC), threaten the integrity of the tanks. Extensive examinations of the type planned should be expected to reveal indications (e.g. potential flaws or cracks) that will require engineering evaluation. If information on crack growth rate is available, predictions of future growth of a detected flaw by stress corrosion can be made. For example, the time at which a growing crack would penetrate the tank wall and produce a leak could be estimated. A small leak to the annulus space does not appear to be unacceptable from the standpoint of short-term impact on safety or the environment. However, if leakage means the tank must be removed from service, there could be an adverse impact on achieving programmatic objectives. The crack growth calculations would also be a basis for determining the schedule for a subsequent UT examination that would validate that crack growth predictions are consistent with observed flaw growth in a tank. Crack growth could also be predicted beyond the leak condition to a point at which the crack size reaches the critical size for unstable extension by a purely mechanical driving force. This condition would be viewed as a major structural failure of the tank. These examples illustrate how predictions of crack growth behavior can form part of the total strategy for managing the useful life of DSTs. The present document defines a test program that would provide information needed to perform these kinds of evaluations.

2.0 CRACK GROWTH RATES

2.1 GENERAL CONSIDERATIONS

Sprowls (1992) notes that a crack growth rate (da/dt) of $1E-10$ m/s is commonly used as a threshold for detectable growth in laboratory tests. It would appear that this limiting growth rate is based on optical measurement of crack length. For a steady state growth rate of this magnitude, a small flaw could penetrate the wall of a DST in about 4-6 years. Catlin et al. (1985) report measurement of crack growth rates as low as $3E-12$ m/s using a reversing d-c potential technique. At this growth rate, it would take over 100 years for a flaw to penetrate the wall. Clearly this greater sensitivity enhances the applicability of the results to actual engineering problems like prediction of tank life.

Crack growth rates can be determined either in constant extension rate tests (CERT) on smooth or precracked specimens or in fracture mechanics tests on precracked specimens that are statically loaded (Parkins 1979, Parkins 1984, Sprowl 1992). CERTs require multiple specimens for determination of

average crack growth rates over some strain or stress range. Fracture mechanics tests are more amenable to determination of instantaneous crack growth rates, but available information indicates that the da/dt values are frequently not a basic material property, but may be multi-valued function of the stress intensity factor and therefore may depend on specimen configuration and test methods (Wei and Novak 1987, Judy et al. 1990, Lisagor 1984, Finnegan and Hart 1976, Wei et al. 1972).

2.2 EXISTING DATA ON MILD STEELS

The existing crack growth data on mild steel in hot nitrate solutions used in developing this test program were published in a series of Savannah River Laboratory (SRL) reports. These reports presented results of fracture mechanics tests on precracked specimens of ASTM A 285 steel (Donovan 1977a and Donovan 1977b) and ASTM A 516 Grade 70 steel (Sarafian 1975). These materials exhibited a Stage II crack growth behavior (crack growth rate is essentially a constant independent of the applied stress intensity factor, K) with a nominal growth rate of about $1E-8$ m/s at 95 C. (Note: the Donovan papers contain obvious discrepancies between units in graphical and tabular presentations; the present assessment is based on the premise that the correct Stage II crack growth rate is about $1E-8$ m/s, as reported by Sarafian (1975). The range of actual measurements appears to be from $0.67E-8$ m/s to $1.15E-8$ m/s.) Sarafian (1975) detected Stage I crack growth in which da/dt decreased rapidly with decreasing K . Donovan (1977a and 1977b) did not detect a Stage I behavior, but reported that crack growth stopped abruptly to terminate Stage II. These differences in crack growth may be related to the differences K_{ISCC} (threshold stress intensity for SCC) reported by the two authors. Both authors reported Stage III behavior in which da/dt increased with K , although neither author used a reliable quantitative measure of crack growth rate in the Stage III regime. Sarafian (1975) and Donovan (1977a) both report crack growth rate decreases at lower temperatures, but give slightly different quantitative descriptions of the decrease.

3.0 RECOMMENDED TEST PROGRAM

The recommended test program is summarized in Table 1. A detailed rationale supporting this program is provided in the following discussions.

3.1 TEST METHOD

The fracture mechanics test method is selected because it provides a good opportunity for definitive measurement of crack length, and it provides for a direct comparison with existing data from SRL. The available fracture mechanics test types include constant-load, constant-displacement, or controlled-load. Each of these test methods requires a measurement of crack growth. As noted earlier, optical methods of crack growth lack the desired measurement sensitivity. The electric potential method offers excellent sensitivity, and the actual potential applied to the specimen can easily be small enough that the effect on the electrochemical potential in the corrosive solution is unimportant. The unloading compliance method of crack length is

often used in fatigue or fracture toughness testing, but the measurement sensitivity appears to be inferior to that attainable by electric potential. In addition, the load cycling necessary for this measurement could lead to an acceleration of the crack growth rate.

In a constant load test, the applied load is typically a dead weight (often acting through a lever arm) that is known accurately. The stress intensity factor (K), determined by the stress, the specimen geometry, and the crack size, increases throughout the test in response to the increase in crack length. Often a long incubation time precedes the start of crack growth and makes it very difficult to obtain measurable crack growth at low K values. Load increments can be added to the specimen after an initial hold period during which no measurable crack growth occurred (incubation time is typically shorter at higher K levels), but it is advisable to consider additional fatigue precracking to make sure that the prior exposure to the corrosive solution did not blunt the crack tip. It is also possible to incrementally reduce the load after crack growth is initiated in order to measure growth rates in a K -decreasing mode. However, care should be taken that the load is not reduced into the regime where plastic deformation in the wake of a growing crack can lead to some closure of crack surfaces while the load is still positive. Since a crack cannot propagate while it remains closed, the net effect of closure is to reduce the applied K value to some lower effective value at the crack tip.

In a constant displacement test, the value of K decreases as crack growth proceeds. The applied load is typically not measured directly, and there are a number of problems that may interfere with an accurate determination of the applied load (which decreases as the crack grows) (Wei and Novak 1987, Judy et al. 1990, Domack 1990). Instrumentation of the loading bolt with strain gages to measure load directly is possible, but has alternately been reported as successful (Gilbreath and Adamson 1976) and as subject to significant error (Judy et al. 1990). The potential for error in the load determination rules against use of this test method for the current program.

Tests can also be conducted in a controlled-load mode. In this case, the specimen is mounted in test frame that has a load cell to measure load and control mode that can be programmed to a desired time-dependence for the load. Fracture mechanics tests are frequently performed in servohydraulic test machines. This capability permits smooth, monotonic load variations, rather than the incremental step changes (with the attendant possibility for small overload due to faulty handling) required with constant-load equipment. In addition, fatigue loading can be imposed to re-sharpen the crack after a hold time in which no growth occurs, or to stimulate crack growth to reduce a long incubation period. If such a system is equipped with a computer that can be used with feedback control from the crack length measuring signal, then tests can actually be conducted at constant K (e.g. see Van Der Sluys and Futato (1985)). This test method offers an advantage for clear characterization of the crack growth process.

The low-strength steels used in DST construction can lead to significant plasticity at the crack tip that can adversely affect the conduct and interpretation of any of the tests described above. If high starting loads cause large plasticity in the constant-load test, a plasticity contribution to crack opening displacement (COD) is introduced (Sarajian 1975) such that crack

length can no longer be accurately assessed from COD measurements. In the case of a constant-displacement test, this plasticity problem means that the load can not be accurately assessed from COD, so the decreasing K values during the test are not known accurately. In addition, under some conditions, values of K_{ISCC} determined from final loads measured indirectly at the end of the test may not be valid for use in linear elastic fracture mechanics calculations (Novak 1973). Unfortunately, the electric potential method may also be subject to errors arising from large plasticity at the crack tip (Bicego et al. 1990).

As a result of an interlaboratory test program conducted to support development of ASTM test procedures for SCC, Wei and Novak (1987) concluded that, because of significant crack tunneling and significant asymmetry in crack growth in some cases, and (more importantly) because the validity of computed K values could not be ensured, meaningful da/dt versus K data could not be obtained from bolt-loaded tests on high-strength steel. For this reason, the constant-displacement test method is rejected for the present task plan.

3.2 MATERIALS

The material selected for the bulk of this program is ASTM A 516 Grade 70 steel in the form of one-inch thick hot-rolled plate. The material should be heat treated for one hour at 593 C (1100 F) to simulate the postweld heat treatment used in tank construction. Material produced to this specification, or to the companion specification ASTM A 515, but at a lower strength grades was used in the earlier Hanford DSTs and has been in service for the longest time. In addition, the work of Sarafian (1975) indicates K_{ISCC} and da/dt are basically similar to that measured in ASTM A 285 Grade B by Donovan (1977a and 1977b). An ASTM A 537 Class 1 steel simulating material used in later DSTs is also selected for limited testing. Sarafian (1975) found that A 516 Grade 70 heat treated to produce a high yield strength (i.e., like that expected in A 537 Class 1) was considerably more resistant to SCC than the hot-rolled material. If this behavior is demonstrated for A 537 Class 1, there may not be a need for an extensive test program on this steel. It would be desirable to conduct the test program using steel produced at about the same time as the steels used in tank construction. Over the intervening years, there have been changes in steelmaking technology. Resultant changes in trace element content achieved by current practice could possibly lead to increased resistance to SCC. Since left-over steel from original construction was not retained, the test program must be conducted using new steel representative of current practice.

Welds and the heat-affected zone adjacent to welds are frequently important to the behavior of welded structures because these regions may exhibit different properties or may contain flaws or defects that influence failure. However, it is also necessary to establish a sound understanding of the behavior of base metal against which weld behavior can be compared. Tests of welds or heat-affected zone (HAZ) effects are not included in this program, but could be included in a follow-on program once base metal behavior is established.

3.3 SPECIMENS

Specimens should be prepared to the appropriate geometry (compact tension, CT, or cantilever bend, CB, are the most logical candidates) with a thickness (B) of one inch. Specimens should be oriented for crack growth in the LT direction (i.e. crack plane will be perpendicular to the rolling direction and crack growth will be in the long-transverse direction). Crack growth leading to wall penetration proceeds in the short-transverse. Any tests to determine anisotropy in crack growth rates between the long-transverse and short-transverse directions is left to a follow-on program. Specimens should be face-grooved, as Donovan (1977b) reported the grooves eliminated crack tunneling. Specimens should be fatigue precracked in accordance with a test procedure that limits the maximum K value used in precracking to not more than 50 percent of the starting K value for the actual test.

3.4 ENVIRONMENTAL CONDITIONS

All of the SRL results for fracture mechanics tests were obtained in solutions containing at least 5 M NaNO_3 . In order to provide a direct comparison with the SRL results, a few tests in 5 M NaNO_3 at 95 C are selected for this program. Twelve of the Hanford DSTs have nitrate contents in the range 1.3 M to 3.8 M, while nine of the DSTs have nitrate contents below 0.6 M (Van Vleet 1993). The CERT studies reported by Ondrejcin (1978) indicated that stress corrosion cracking in simulated waste solutions did not occur in these severe tests if the nitrate content was below about 2.2 M (solutions contained no nitrite or hydroxide). However, Danielson and Bunnell (1994) found SCC did occur in two solutions low in nitrate (0.4-1.0 M) if nitrite and hydroxide were also low. Therefore, solutions with several nitrate compositions were selected for this program to extend observations to nitrate levels more representative of DST conditions.

The basically pure nitrate solutions were used in the original SRL testing because they are more aggressive than solutions containing significant quantities of hydroxide and/or nitrite that are more representative of DST wastes. Donovan (1977b) employed solutions containing up to about 1 M (hydroxide plus nitrite), and found that resistance to crack propagation increased markedly by extending the incubation time required to initiate crack growth. The wastes in the DSTs containing high nitrate levels generally exhibit combined hydroxide plus nitrite levels that are much higher than 1 M. However, the Ondrejcin (1978) CERT studies indicated that SCC might be possible in solutions with the higher hydroxide and nitrite levels representative of DSTs if the temperature was in the range of 60-80 C, but SCC was not indicated at a temperature of 100 C. This information led to the selection of three solutions high in hydroxide and nitrite for the present program.

3.5 TEST PROCEDURE

Detailed test instructions for the conduct of the test program can be modelled after those used in the ASTM round robin program on stress corrosion racking in 4340 steel (Wei and Novak 1987). Even though some important changes will be necessary, use of the round robin instructions as a model will help ensure that important details are not overlooked.

The first constant-load or controlled-load test can be initiated at a reasonably low K (load) level, but if crack growth is not detected after a pre-determined hold time (e.g. 100 or 200 hours), the load can be increased to produce a higher, specified K level. This process can be repeated until crack growth is detected. Once crack extension begins, the load can remain fixed for the duration of the test (in which case K continues to increase with crack length), or incremental load increases can be imposed to increase K while avoiding long test durations. Depending on the sensitivity of crack length measurement, it may be possible to then reduce load on this specimen to extend the da/dt measurements to as low a level as possible. In a controlled-load test with feedback control, it may be feasible to alternately decrease and increase load to reveal transients in crack growth rate, as well as to measure steady-state growth rates as a function of K. However, the test program provides for a second specimen in the event that all the desired range cannot be covered with a single specimen.

Test duration will be determined by the sensitivity of crack length measurement (and possibly by transients in da/dt when using constant K testing). Catlin et al. (1985) indicate that testing to measure crack growth rate at several different K levels, with the lowest da/dt approaching $7E-13$ m/s, required less than one month's time using reversing d-c electrical potential measurement. Test time to measure the higher crack growth rates that are also of interest should be very short, so total test time of 4-5 weeks should be possible.

3.6 TEST PRIORITIES

Test priorities from A (high) to D (low) are given in Table 1 to identify the relative importance of the various tests. The tests in nitrate solutions are priority A because they have the highest probability to produce measurable crack growth. One test in solutions with high hydroxide and nitrite is priority B because the probability for crack growth is lower. The other two tests in the high hydroxide and nitrite solutions are priority C because one or both of these tests could be eliminated if the priority B test fails to exhibit measurable crack growth. Tests to determine the effect of temperature on crack growth in nitrate solutions are priority D because they are intended primarily to clarify the differences in temperature dependence reported in SRL results.

4.0 COST AND SCHEDULE

The recommended test program will be implemented by a test performer under contract to WHC. The following subsections provide estimates of the anticipated cost and schedule pending actual responses from potential performers.

4.1 COST ESTIMATE

<u>Activity</u>	<u>Cost, \$1,000</u>
Materials and specimen preparation	30
Solution preparation, containment, control	15
Developmental testing	15
Data generation testing	200
Data reduction, analysis, reporting	<u>40</u>
Total	300

4.2 SCHEDULE ESTIMATE

<u>Activity</u>	<u>EIapse Time, Weeks</u>
Specimen preparation	4-6
Equipment set-up	4-6
Development tests	6-8
Data generation tests	10-72
Data analysis and reporting	68-76

The above schedules are estimated for a single test system; multiple test systems would shorten schedule.

WHC procurement activities leading to contract award are estimated to require 4-6 weeks.

Table 1. Test Program.

Test Priority	Temp, °C	Solution Composition, M			Number of Specimens	Material	
		NO ₃	NO ₂	OH		A516 Gr. 70	A537 Class 1
A	95	5.0			2	✓	✓
A	95	3.0			2	✓	
A	95	0.4			2	✓	
D	80	3.0			2	✓	
D	60	3.0			2	✓	
B	80	3.0	1.2	2.4	2	✓	
C	80	3.0	2.0	4.0	2	✓	
C	80	3.0	2.0	1.2	2	✓	

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