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# BLOWDOWN TRANSIENTS AND IMPLICATION FOR LEAK PROTECTION SHUTDOWN STRATEGY

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# BLOWDOWN TRANSIENTS AND

# IMPLICATION FOR LEAK PROTECTION SHUTDOWN STRATEGY

## 1.0 INTRODUCTION

The FY-1980 follow-on study of leak protection for post-CRBRP steam generators has as its general objective the investigation of possible means of initiating automatic shutdown in the event a sodium-water reaction is detected. The ultimate goal is to establish a reliable automatic shutdown method, acting prior to rupture disc actuation, that will significantly reduce the damage to the affected steam generator and intermediate heat transport system (IHTS) below that which would be sustained if no such automatic shutdown were available. In addition, the shutdown method is to minimize the overall damage from all causes. For example, the wastage damage from a long shutdown must be balanced against the creep-fatigue damage due to a quick shutdown.

Of concern to the development of an optimum leak protection shutdown strategy is the severity of the selected blowdown transient(s). The ability to utilize automatic shutdown and the choice of leak rate alarms may be dependent upon the character of the blowdown transient used and the resulting amount of stress damage in critical areas of the steam generators and other IHTS components.

This report documents a study of blowdown transients and implications for leak protection. The Clinch River blowdown transient (SG-07U) is used as a baseline for this study as it is typical and has been more thoroughly analyzed than transients for any of the post-CRBRP steam generators. The CRBRP shutdown strategy, the details of the blowdown transient, and the allotted number of blowdown transients are summarized in Section 2. The amount of stress damage due to the blowdown transients is given in Section 3; based on the per-transient damage, a total allowable number of transients is defined. Section 4 discusses selection of a water-side blowdown transient for future plants where automatic shutdown may be employed. A summary of the major conclusions of the study are presented in Section 5.

## 2.0 BLOWDOWN TRANSIENT

### 2.1 Allotted Number of Blowdowns

The CRBRP Steam Generator Equipment Specification [1] specifies 29 water-side blowdown transients per loop over the 30 year plant life. These are classified as upset events and are as follows:

| | | No. of Events |
|---|---|---|
| SG-06U | Water-side isolation and blowdown of an evaporator module | 7 |
| SG-07U | Water-side isolation and blowdown, superheater and both evaporators | 6 |
| SG-11U | Evaporator outlet relief valves open | 3 |
| SG-12U | Superheater outlet relief valves open | 13 |
| | | 29 |

Of these, only the 13 SG-06U and SG-07U transients are associated with leak protection. The other 16 blowdown transients are the results of other upset events, including operator error.

In addition, there are four possible emergency events with blowdown from full power conditions:

| | |
|---|---|
| SG-01E | Isolation and blowdown of a superheater, inlet valve fails to close. |
| SG-03E | Design basis steam generator sodium-water reaction. |
| SG-05E | Superheater isolation and blowdown, outlet isolation valve open |

SG-08E Isolation and blowdown of an evaporator module, inlet isolation valves fails to close

A maximum of seven emergency events, of all types, is allowed. The emergency events are not considered in this study.

## 2.2 Leak Protection Strategy

The protection strategy following detection of a small water-to-sodium leak adopted by CRBRP in SDD-53 [2] can be taken as representative of LMFBR practice:

- For leaks of $2 \times 10^{-5}$ to $6.5 \times 10^{-3}$ lb/sec, the reactor is scrammed. The sodium temperatures in the IHTS drop to standby conditions (600°F). When the sodium temperature difference reaches 50°F (about 15 minutes after scram), the affected steam generator will be isolated and blown down on the water side.

- For leaks of greater than $6.5 \times 10^{-3}$ lb/sec, a rapid water-side isolation and blowdown (SG-06U or 07U) is initiated immediately.

- If, in the case of a small leak where the reactor is scrammed, the leak enlarges to greater than $6.5 \times 10^{-3}$ lb/sec, a rapid water-side isolation and blowdown is initiated immediately.

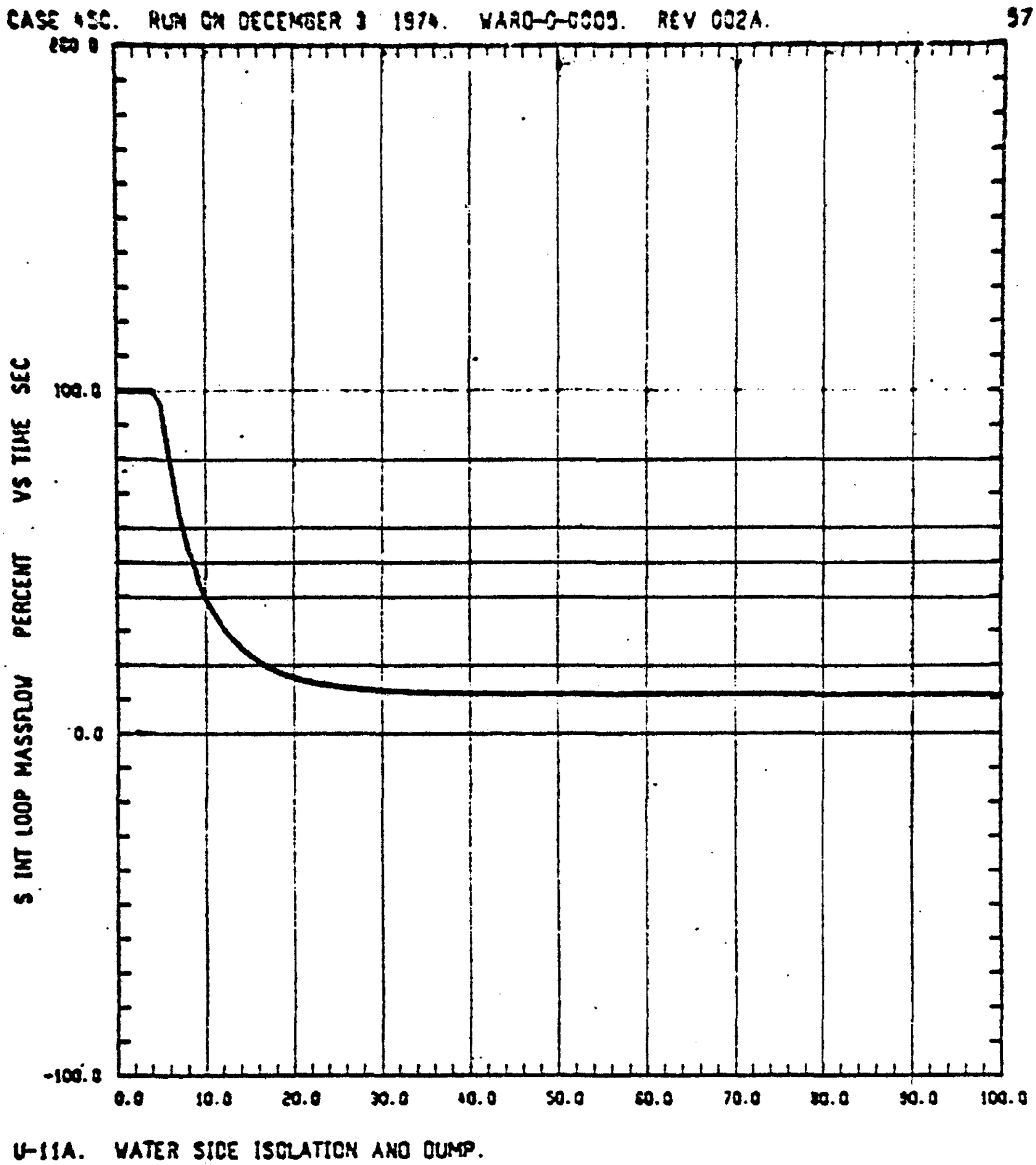
Any discussions of transient modification must start from a clear understanding of the isolation and blowdown transient. The blowdown of all three heat exchange units in a loop (i.e., SG-07U) will be described in detail, as it is believed that it will not be possible in the majority of leak detection cases to identify quickly which unit has the leak.

## 2.3 Isolation and Blowdown Sequence

Following detection of a relatively large small leak (>$5 \times 10^{-3}$ lb/sec), the SG-07U transient is initiated by a signal which (1) closes the normally open isolation valves in the inlet water lines to the evaporators and in the inlet and outlet steam lines of the superheater and (2) simultaneously opens the dump valve in the water-side inlet to each evaporator and the power relief valves in the evaporator and superheater water/steam side outlets. A reactor trip occurs approximately 4 seconds after the isolation valves shut due to steam-flow/feed-flow mismatch. The rapid reduction in evaporator pressure closes the check valve in each evaporator outlet line prohibiting backflow from the drum. The water/steam side pressure decreases until the power relief and dump valves shut. Nitrogen purge gas valves open and the water-side of the units is backfilled with nitrogen when the pressure drops to a low value.

The water pressure at the evaporator inlet falls to atmospheric pressure in ∿3 seconds. The pressure within the heat exchange units reduces in ∿20 seconds. The steam flow into the superheater drops to essentially zero in less than 2 seconds. The inlet water flow to the evaporator stops and reverses to ∿135% of its original, steady-state value and then rapidly falls to zero, within 5 seconds of transient initiation.

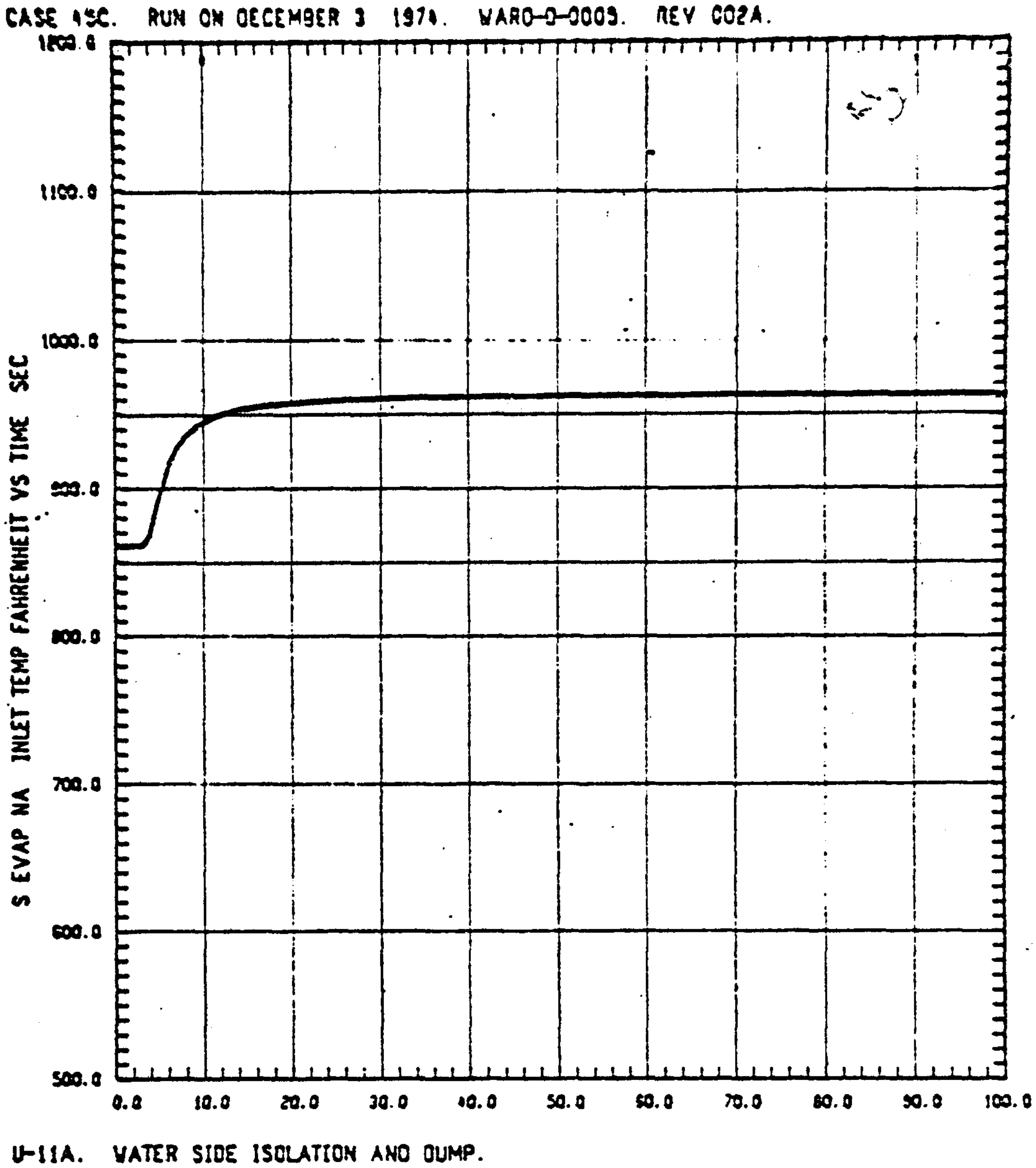
On the sodium side, the sodium flowrate remains constant at its steady state value until the reactor scram (at 4 sec) and then decreases to 40% flow at 10 seconds and to close to its final value of ∿10% flow within 40 seconds (see Figure 1). With the loss of water-side flow, the heat removal capabilities of the units disappear and, consequently, sodium temperatures (and steam generator metal temperatures) rise to that of the sodium exiting the intermediate heat exchanger (IHX). Sodium temperature rises are first seen in the evaporators. The inlet sodium rises from 860 to 960°F in 20 seconds (Figure 2). These increases continue until, at 500 seconds, 1000°F is reached and then the entire intermediate loop begins to cool. The superheater response is delayed because of its relatively higher temperatures. The sodium inlet remains at ∿960°F for 200 seconds and then increases to 1000°F at 300 seconds (Figure 3). After 500 seconds, the entire intermediate loop cools.




SG-7UF1
SG-7UF2

FIGURE 1

IHTS SODIUM FLOWRATE DURING TRANSIENT SG-07U




EV-7UT1

FIGURE 2

EVAPORATOR SODIUM INLET TEMPERATURE DURING TRANSIENT SG-07U

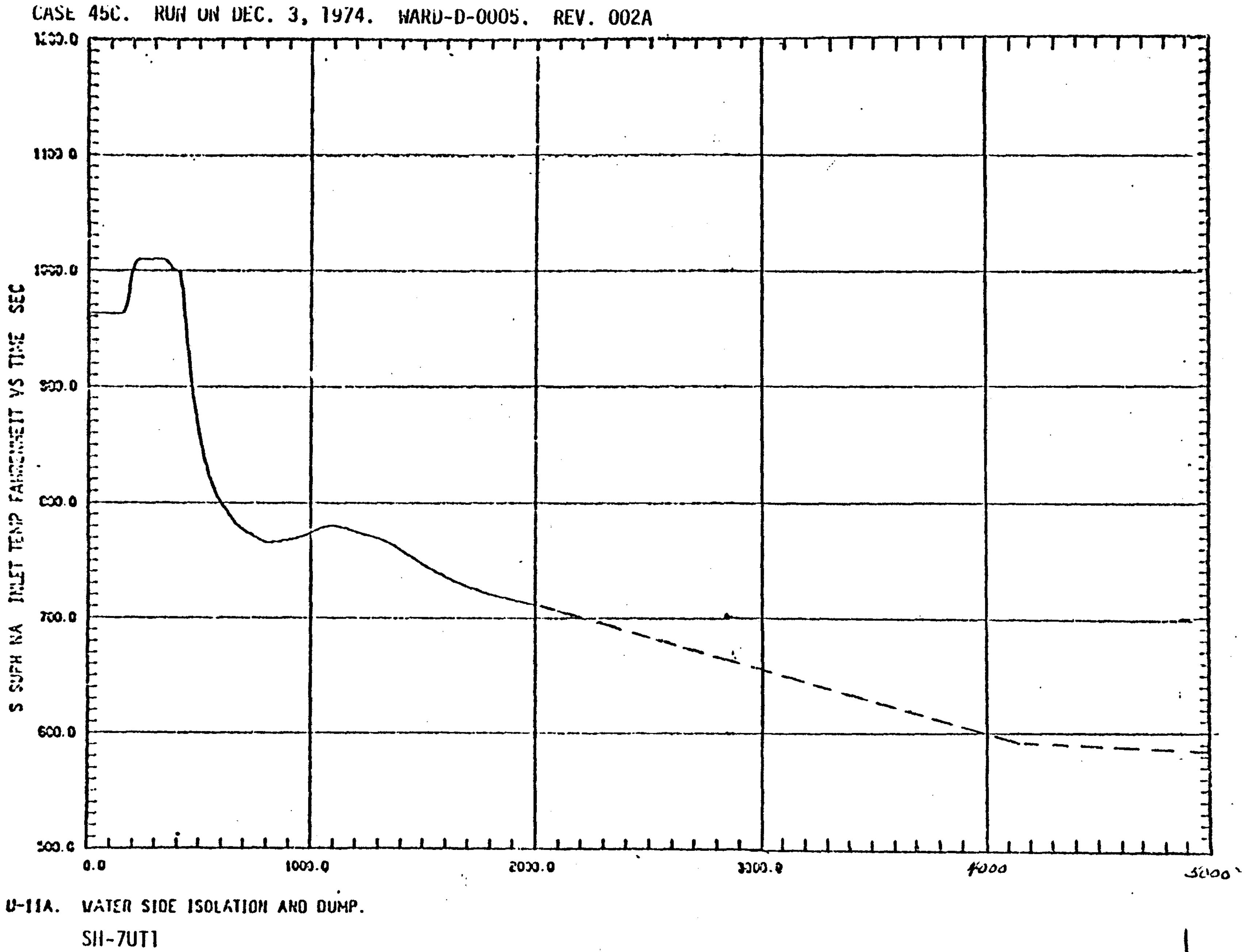



FIGURE 3

SUPERHEATER SODIUM INLET TEMPERATURE DURING TRANSIENT SG-07U

## 3.0 DAMAGE DUE TO BLOWDOWN TRANSIENT

### 3.1 Heat Exchange Units

A preliminary analysis of stress damage to the CRBRP heat exchange units due to an "umbrella" blowdown transient has been made by Atomics International [3, 4]. This umbrella transient is a worst case approximation to the various blowdown transients and specifically includes the SG-06U and SG-07U transients. (It should be noted that the AI stress analysis is preliminary and could be revised by results of a complete elastic analysis.)

Primary stresses are low enough to be of no concern. However, creep-fatigue damage must be considered for the relatively massive tubesheets. Of these, the worst is the superheater upper tubesheet because its normal operating temperature is above 700°F.

The AI analysis calculates that the total creep-fatigue damage factor, from <u>all</u> transients, on the superheater upper tubesheet is 0.794. However, only 0.151 of the damage factor is due to the 29 blowdown transients. Each blowdown transient contributes no more than 0.0052 (0.151/29) damage. It should be noted that when one loop undergoes a blowdown transient, the other two loops are subjected to a normal reactor scram transient (SG-01U). However, as calculated by AI, the creep-fatigue damage due to a normal reactor scram is negligible and does not contribute to the total damage factor.

The damage from the blowdown transients is due to the large ΔT's that are set up across the upper primary and secondary tubesheets by the high heat capacity of the tubesheets and their slow cooling following a reduction in sodium temperature at the primary tubesheet. In cases such as SG-07U where the CRBRP superheater has been isolated and dumped on the water side, these ΔT's are relatively low and, in fact, are less than for the standard reactor scram (SG-01U). Stress problems occur when appreciable superheater steam flow is maintained during the transient. The worst case is SG-06U: isolation and dump of one evaporator. Water flow is maintained through the active evaporator and a reduced steam flow is maintained through the superheater. The resulting heat transfer pulls the IHTS sodium temperatures down more rapidly than when all three units are dumped (i.e., SG-07U) and results in larger superheater tubesheet $\Delta T$'s and creep-fatigue damage.

The time variation of $\Delta T$'s across the superheater primary upper tubesheet is shown in Figures 4 through 6 for transients, SG-07U, SG-06U and SG-01U, respectively. A summary of maximum $\Delta T$'s for various transients is given in Table 1. These figures and table are reproduced from the AI tubesheet transient report [9].

Extrapolation of CRBRP transients and damage increments to large LMFBR's, which may be once-through units, perhaps run in parallel, must be done with care. The CRBRP analysis concludes that the creep-fatigue damage from one "umbrella" blowdown transient is quite small (0.0052) and for the SG-07U transient, in which the superheater is blown down, is even less, being no more than for a reactor scram.

The damage factor numbers in isolation would suggest that a significantly larger number of leak protection blowdown transients might be accepted by the heat exchange units than is currently specified. The limiting damage factor is one; for conservatism a design limit of 0.9 is used. On this basis, an additional 20 blowdown transients of SG-06U severity could be accommodated. by the CRBRP superheater. The total number of allowable leak protection blowdown transients would then be 33, or greater than one per year. Even greater numbers of blowdown transients similar to SG-07U could be accommodated.

Very similar isolation and blowdown transients are anticipated for future LMFBR's [10]. A creep-fatigue analysis similar to that done for the CRBRP units must be conducted for each advanced steam generator design, considering the mass and thermal capacity of the tubesheets, to assess the number of blowdown transients allowable. However, it is anticipated that with reasonable design practices, the design margins will be similar to those for the CRBRP units.

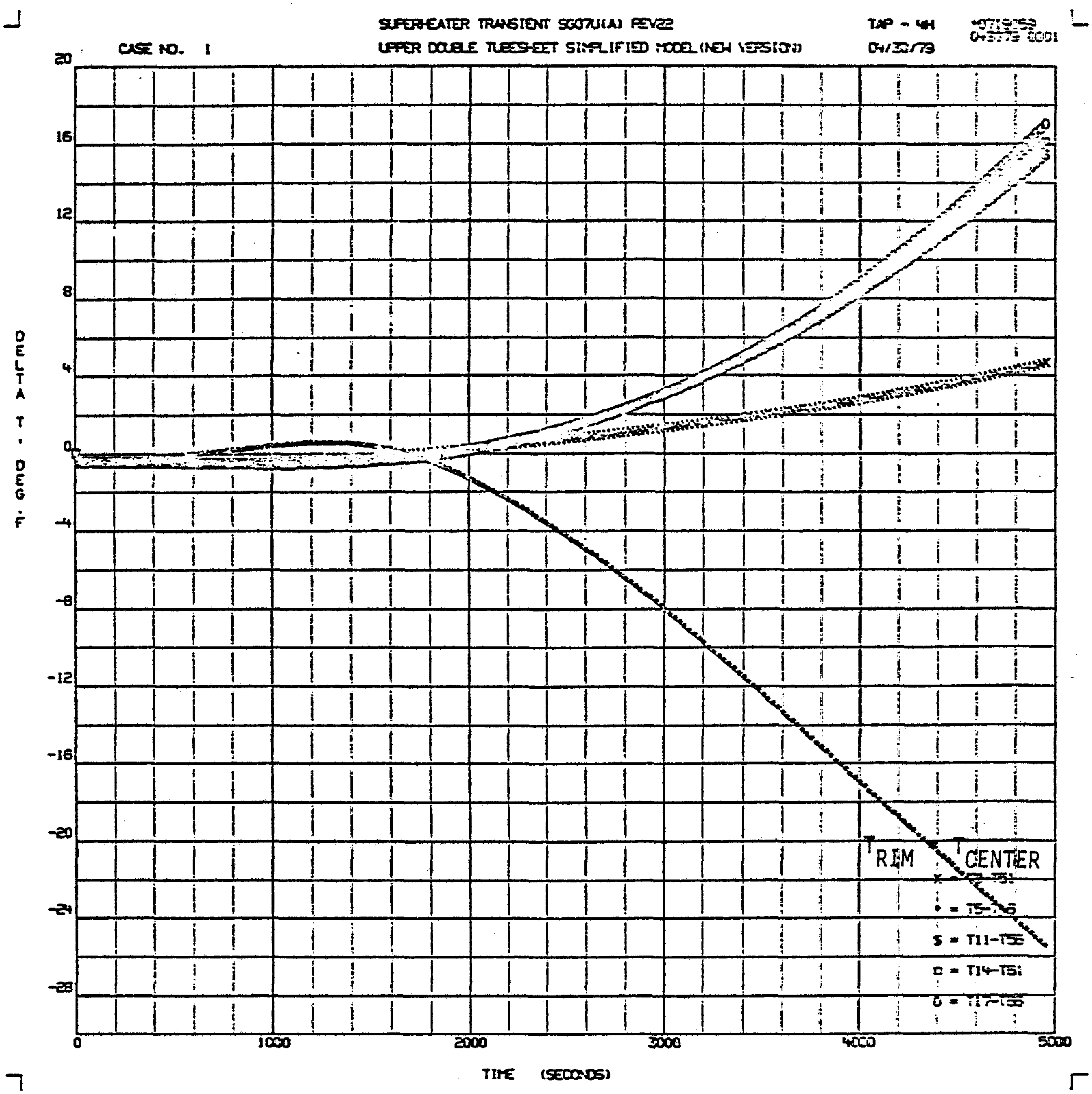



FIGURE 4

SUPERHEATER UPPER TUBESHEET ΔTs DURING TRANSIENT SG-07U
(ISOLATION AND BLOWDOWN OF ALL THREE HEAT EXCHANGE UNITS)

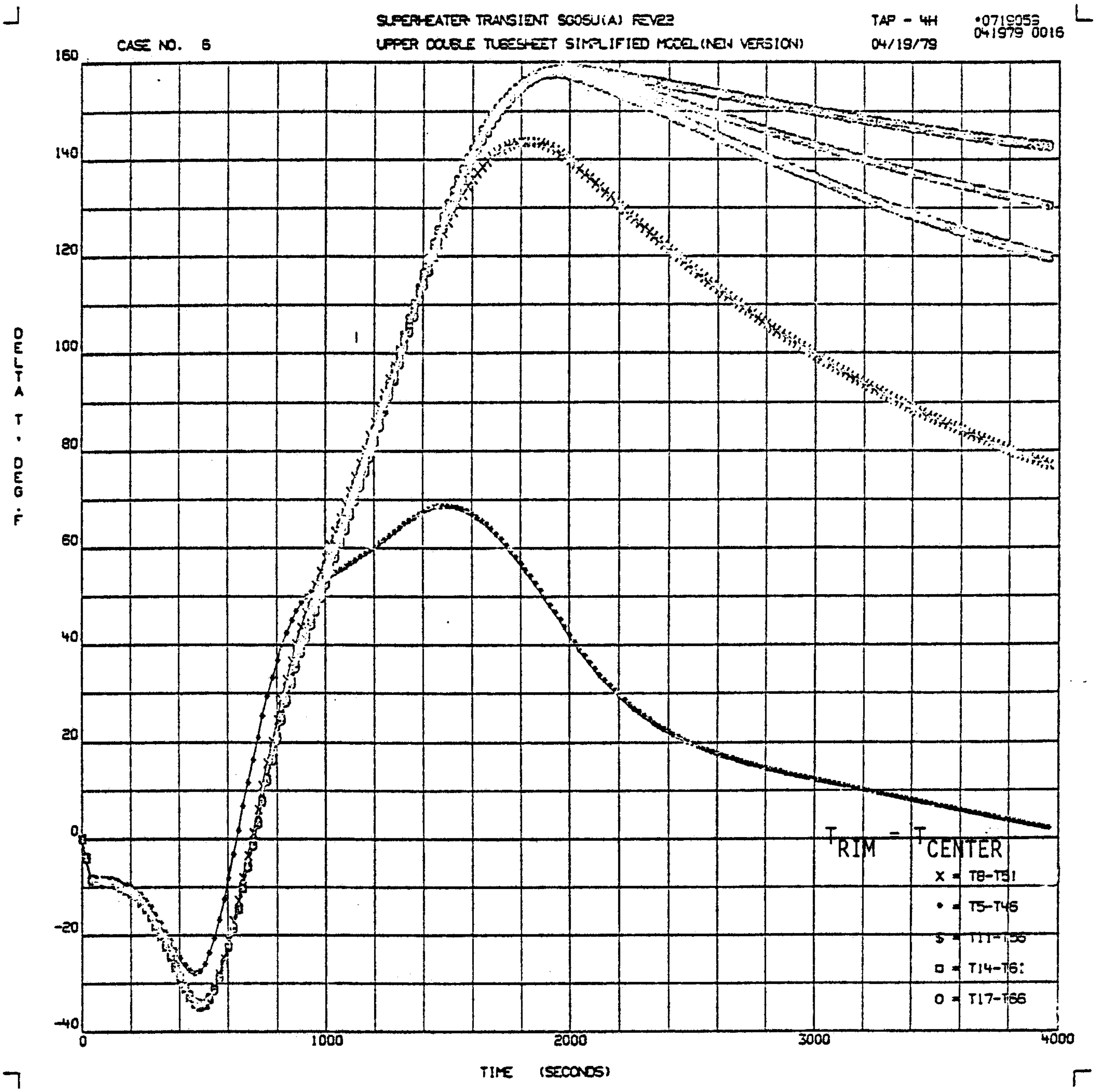



FIGURE 5

SUPERHEATER UPPER TUBESHEET ΔTs DURING TRANSIENT SG-06U
(ISOLATION AND BLOWDOWN OF ONE EVAPORATOR)

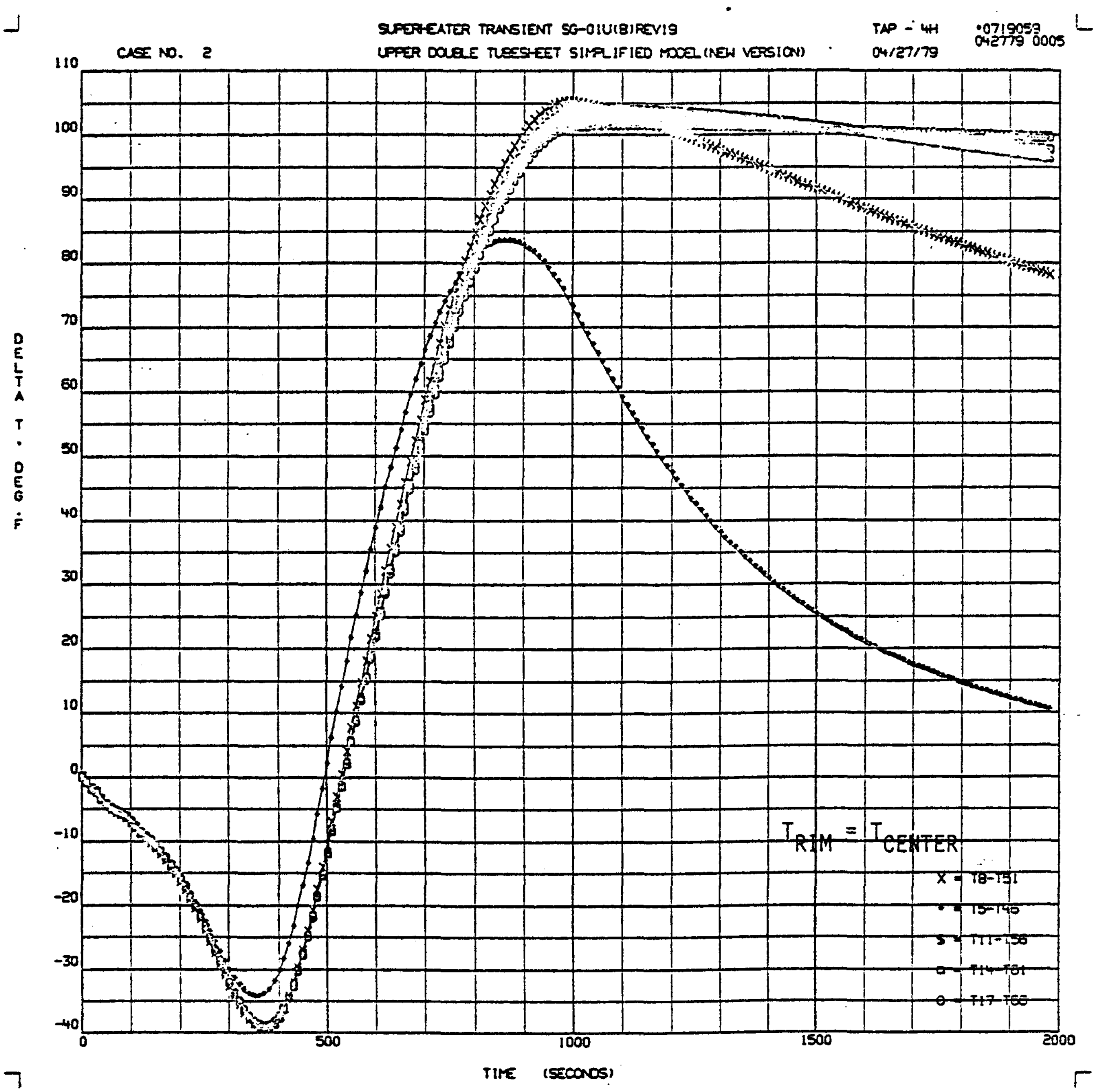



FIGURE 6

SUPERHEATER UPPER TUBESHEET ΔTs DURING TRANSIENT SG-01U
(REACTOR SCRAM)

TABLE 1

SUPERHEATER - UPPER DOUBLE TUBESHEET

$\Delta T = (T_{Rim} - T_{Center})$

[From Reference 9]

| | Tran. | Primary Tubesheet $\Delta T_{Max.}$ (°F) | Time (sec) | $\Delta T_{Min.}$ (°F) | Time (sec) | Secondary Tubesheet $\Delta T_{Max.}$ (°F) | Time (sec) | $\Delta T_{Min.}$ (°F) | Time (sec) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Normal Conditions | | | | | |
| 1 | SG03N | 3.6 | 1,800 | -131.6 | 21,750 | 0.0 | 0 | -182.4 | 21,750 |
| 2 | SG04N | 123.8 | 7,400 | -11.7 | 24,400 | 166.5 | 7,400 | 0.0 | 0 |
| 3 | SG05N | 0.0 | 0 | -126.4 | 7,200 | 0.0 | 0 | -164.4 | 7,300 |
| 4 | SG06N | 122.5 | 7,100 | -8.3 | 200 | 160.9 | 7,200 | -8.3 | 200 |
| 5 | SG08N | 27.7 | 3,390 | -39.1 | 4,860 | 30.5 | 3,420 | -36.2 | 4,950 |
| 6 | SG09N | 0.0 | 0 | -10.1 | 160 | 0.0 | 0 | -10.1 | 283 |
| | | | | Upset Conditions | | | | | |
| 7 | SG01UA | 77.5 | 1,180 | -36.8 | 350 | 76.1 | 1,230 | -36.6 | 350 |
| 8 | SG01UB | 105.2 | 990 | -39.4 | 370 | 102.8 | 1,030 | -39.3 | 370 |
| 9 | SG01UC | 102.7 | 1,000 | -38.9 | 380 | 100.3 | 1,040 | -38.8 | 380 |
| 10 | SG01UD | 257.5 | 1,520 | -39.4 | 360 | 258.6 | 1,540 | -39.2 | 360 |
| 11 | SG02U | 175.4 | 820 | -8.5 | 70 | 176.6 | 840 | -8.5 | 70 |
| 12 | SG03U | 124.2 | 1,480 | -99.1 | 660 | 119.6 | 1,600 | -99.5 | 660 |
| 13 | SG03UB | 91.8 | 1,580 | -101.2 | 650 | 82.1 | 1,630 | -101.6 | 650 |
| 4 | SG04U | 0.0 | 0 | -213.9 | 620 | 0.0 | 0 | -214.4 | 620 |
| 15 | SG05U | 29.0 | 130 | -47.3 | 910 | 29.0 | 130 | -47.5 | 950 |
| 16 | SG06UA | 157.7 | 1,940 | -34.7 | 480 | 158.5 | 1,980 | -34.7 | 480 |
| 17 | SG07UA | 15.4 | 4,950 | -25.5 | 4,950 | 17.0 | 4,950 | -0.6 | 1,100 |
| 18 | SG07UB | 1.0 | 1,820 | -0.8 | 2,380 | 0.0 | 0 | -0.8 | 2,380 |
| 19 | SG07UC | 3.4 | 1,980 | -12.1 | 1,630 | 3.9 | 1,980 | 0.0 | 140 |
| 20 | SG10UA | 100.7 | 840 | -43.2 | 360 | 116.3 | 3,960 | -43.1 | 360 |
| 21 | SG10UB | 69.2 | 1,080 | -46.5 | 360 | 78.0 | 3,960 | -46.4 | 360 |
| 22 | SG12U | 0.7 | 40 | -7.3 | 320 | 0.7 | 40 | -7.2 | 320 |
| 23 | SG13U | 121.4 | 2,260 | -38.4 | 500 | 126.3 | 2,440 | -38.4 | 500 |
| 24 | SG16U | 46.4 | 500 | -36.6 | 320 | 42.4 | 1,980 | -36.4 | 320 |
| 25 | SG17UA1 | 25.0 | 5,000 | -26.2 | 5,000 | 27.2 | 5,000 | -0.7 | 1,050 |
| 26 | SG17UA2 | 0.9 | 1,700 | -0.6 | 2,220 | 0.1 | 3,200 | -0.7 | 2,320 |
| 27 | SG18UA1 | 12.6 | 3,960 | -15.4 | 3,960 | 13.2 | 3,960 | -0.3 | 1,120 |
| 28 | SG18UA2 | 0.9 | 1,740 | -0.8 | 2,240 | 0.0 | 0 | -0.9 | 2,280 |
| 29 | SG19U | 240.7 | 1,220 | -41.0 | 360 | 240.2 | 1,220 | -40.9 | 360 |
| 30 | SG20U | 220.6 | 1,180 | -42.2 | 360 | 219.5 | 1,180 | -42.2 | 360 |
| 31 | SG21U | 134.8 | 9,300 | -54.0 | 200 | 182.5 | 9,300 | -54.0 | 200 |
| 32 | SG23U | 0.0 | 200 | -98.4 | 920 | 0.0 | 200 | -98.8 | 920 |
| | | | | Emergency Conditions | | | | | |
| 33 | SG01E | 295.0 | 1,610 | -44.1 | 360 | 302.4 | 1,670 | -44.2 | 360 |
| 34 | SG03E | 0.0 | 0 | -34.1 | 360 | 0.0 | 0 | -34.5 | 360 |
| 35 | SG04E | 110.1 | 3,340 | -63.2 | 1,020 | 110.4 | 3,340 | -63.9 | 1,100 |
| 36 | SG08EA | 8.7 | 3,960 | -20.8 | 3,960 | 9.0 | 3,960 | -4.7 | 120 |
| 37 | SG09E | 0.0 | 0 | -14.1 | 92 | 0.0 | 0 | -14.1 | 91 |
| 38 | SG10E | 259.4 | 3,660 | -54.2 | 880 | 274.4 | 3,920 | -54.5 | 900 |
| 39 | SG11E | 4.0 | 1,980 | -19.7 | 1,980 | 3.7 | 1,980 | -7.8 | 50 |

Plant availability considerations may not permit the use of such a large number of "stress-allowable" leak protection blowdown transients as one per year. The cost of plant downtime is great, particularly as the plant operator following shutdown, must determine whether the transient was initiated by a leak detection system false alarm or by an actual leak to be located and plugged. Thirteen to fifteen leak protection transients over the unit's life (as is specified for CRBRP) would seem a reasonable design number -- with every effort expended to reduce the actual number of transients to a much smaller value.

### 3.2 Intermediate Pump

The other major IHTS component, besides the steam generator units which is affected by the blowdown transients is the intermediate pump. A detailed stress analysis of the CRBRP pump has been conducted by Foster Wheeler [8]. For the intermediate pump, the operating temperature is below the creep region (650$^{\circ}$F) and Reference 8 concludes that the limited number of transients which experience elevated temperatures produce negligible creep effects.

For purposes of analysis, the most severe pump upset event (IP-3U) and the remaining "fairly severe" upset transients were lumped with a severe emergency event (IP-6E) to give 98 IP-6E umbrella events. The other, less severe upset transients were grouped with the IP-1U event; the creep-fatigue damage from this event is negligible. An elastic fatigue analysis was done on the 98 IP-6E events. The resulting total fatigue damage was only 0.68, or 0.007 damage per transient. In reality, the upset events will contribute much less to the fatigue damage than the umbrella emergency transient used in the calculations. Additionally, as Reference 8 notes, a more rigorous inelastic analysis would be expected to show a substantial reduction in fatigue damage from that predicted by elastic analysis.

It is concluded that the limiting components for stress damage resulting from blowdown transients are the steam generator units. The remainder of this report will, therefore, consider only these units.

## 4.0 SELECTION OF BLOWDOWN TRANSIENT

Various factors affecting the selection of an optimum blowdown transient have been investigated.

It must first be recognized that, for this class of transients, the creep-fatigue damage is due to the very large thermal capacity of the tubesheets which cause them to lag significantly behind changes in sodium temperature. Each blowdown transient can be divided into two time periods (see Figure 3). In the first, the loss of water-side flow and heat removal capability results in a rise of sodium temperatures for approximately 500 seconds or 8 minutes. The reactor scram and main pump trips, which occur very early in the transient (at ∿4 seconds), eventually result in a decrease in primary loop temperatures and IHTS sodium temperatures. This constitutes the second time period of the blowdown transient. For CRBRP, the second period lasts typically from 8 minutes to one hour, at which time temperatures reach standby conditions of ∿600°F.

These two time periods must be looked at separately. In the first up-temperature phase, the transient severity could be lessened by providing some heat removal capability within the steam generators for an extended period compared to the current transients. This suggests two possible alternatives:

1. Maintain a reduced water/steam flow through the units, or
2. Slow down the blowdown, i.e., decrease the rate of water-side pressure blowdown.

However, maximum tubesheet ΔT's and significant creep-fatigue damage do not occur in this time period.

In the second or cool-down phase, the transient's severity is reduced by decreasing the temperature reduction rate of the perforated region of the tubesheet. This can be done by decreasing the heat transfer from the tubesheet. Steam flow through the upper tubesheet is detrimental; one wants the water-side completely blowdown at this time. Also, one wants the system designed to result in a slow decrease of sodium temperatures after reactor scram and pump trip.

Inspection of the various transient ΔT's generated across the CRBRP tubesheets in Reference 9 (see Table 1 of this report) shows that for almost all upset transients, maximum ΔT's are generated in the second, long-term phase of the transient rather than in the first phase. This is, again, a direct consequence of the relatively massive tubesheets and their large thermal capacities. Figures 4, 5, and 6 reproduced from Reference 10, show this behavior clearly for SG-07U, SG-06U, and SG-01U (reactor scram), respectively.

One conclusion of this study, therefore, is that reasonable variations of the water-side blowdown rate have no effect on the severity of the transient and the resulting stress damage. These are set by the total plant coast-down characteristics after reactor scram. Consideration should be given to terminating the water-side flow shortly after reactor scram as a way to reduce the rate of tubesheet cooldown and to stop further sodium-water reaction wastage damage.

Since the water-side isolation and blowdown does not affect the severity of the overall transient, the blowdown process can be selected on the basis of leak rates and wastage damage alone. The key questions are:

- At what minimum leak size should a rapid blowdown be used?
- If a blowdown is to be used, how fast should it be?

The second question is the easier of the two to answer: The blowdown should be as rapid as practical. This follows from the potential for rapid tube failure propagation at larger leak rates. Using the CRBRP steam generator conditions and a sodium temperature of 860°F as an example, the earliest possible secondary tube failure occurs at 200 sec for a $10^{-4}$ lb/sec leak, at 45 sec for a $10^{-3}$ lb/sec leak and at 15 sec for a $5 \times 10^{-3}$ lb/sec leak. Thirty seconds has been shown to be a feasible and practical blowdown time.

Reactor scram will be initiated upon indication of a small leak (e.g., $>2 \times 10^{-5}$ lb/sec for CRBRP). Because of the economic penalty associated with plant shutdown, there is a strong incentive not to scram. Therefore, one needs to assure that the leak is "real" and not a false alarm from the leak detection system. One way to do this is by confirming the alarm with signals from other leak detection meters.

Once a scram has been taken, there is no further economic penalty associated with a subsequent water-side blowdown. The time for blowdown initiation can be determined by balancing the potential for secondary tube damage against the need for further verification of the leak and location to within a particular unit. At some leak size, the potential for secondary tube damage is so great that rapid blowdown must occur simultaneously with (or precede) reactor scram.

Inspection of wastage limits for the CRBRP heat exchange units and for advanced units suggests that problems with secondary tube failures will become severe at about $3 \times 10^{-4}$ lb/sec if manual shutdown is used. Clinch River wastage limits are plotted in Figures 7, 8, and 9 for sodium temperatures of 650, 860, and 900°F, respectively. In each plot, the solid lines represent the minimum time for wastage failure at each leak rate. The dotted lines represent the average time for wastage failure; that is one-half of the leaks will require more time to failure and one-half will require less time to failure than represented by the dotted curves.*

Minimum time for detection is approximately 60 seconds, based on first-pass detection with the reference CRBRP chemical leak detectors. To this must

*The data base and rationale for the wastage curves are given in Appendix A.

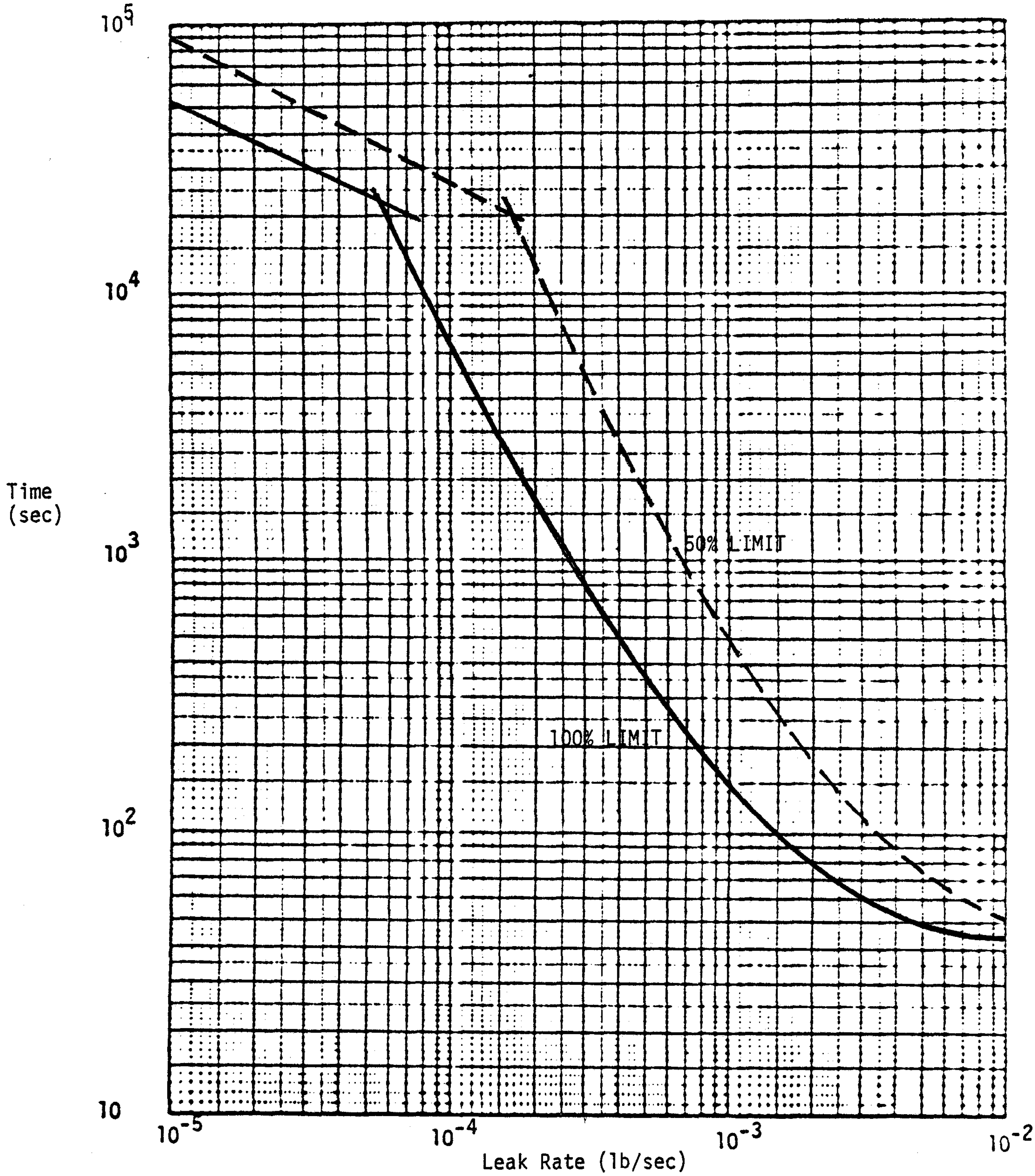



Figure 7 650°F Wastage Limits for CRBRP Evaporator, Main Body

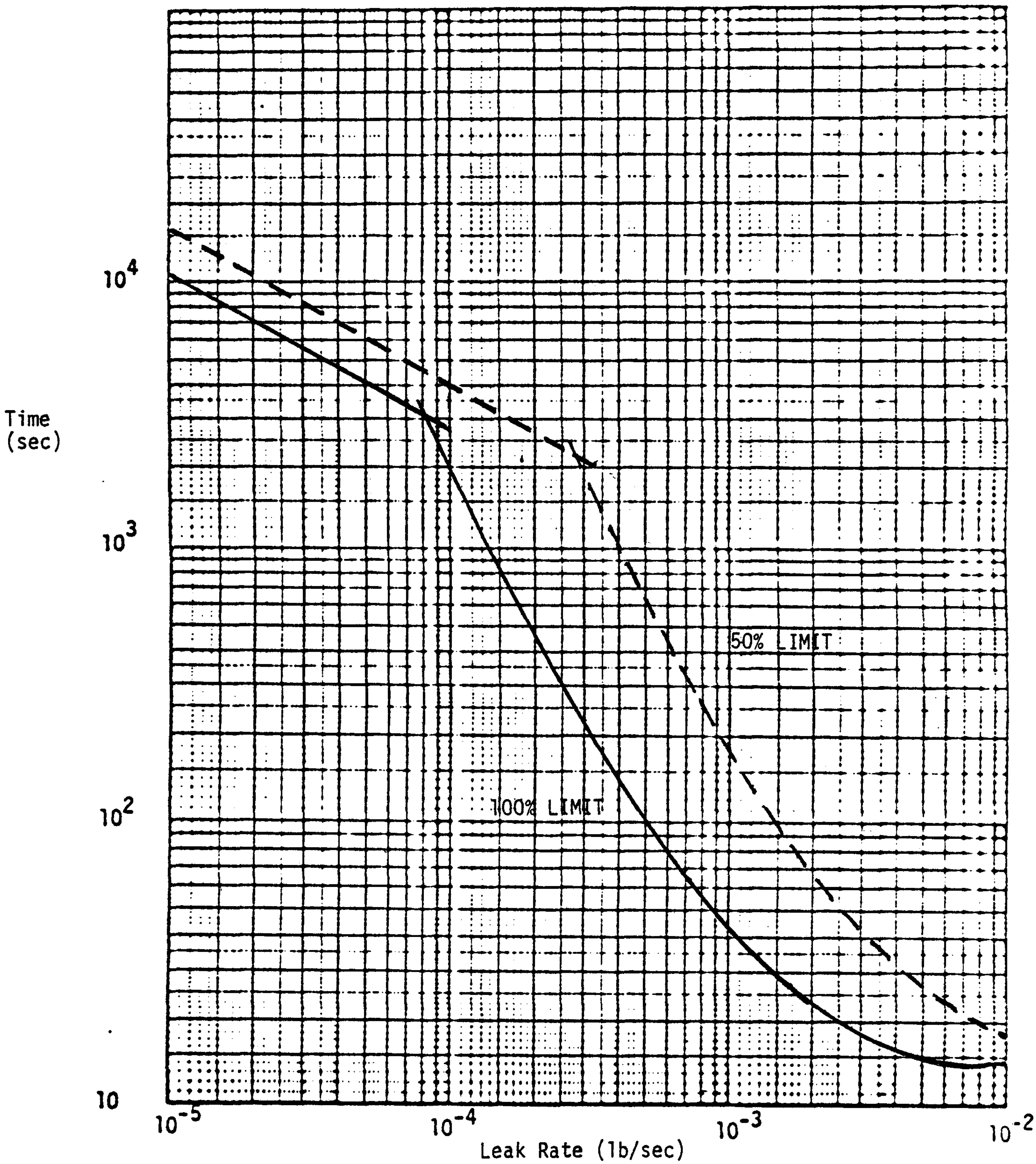



Figure 8. 860°F Wastage Limits for CRBRP Evaporator/Superheater, Main Body

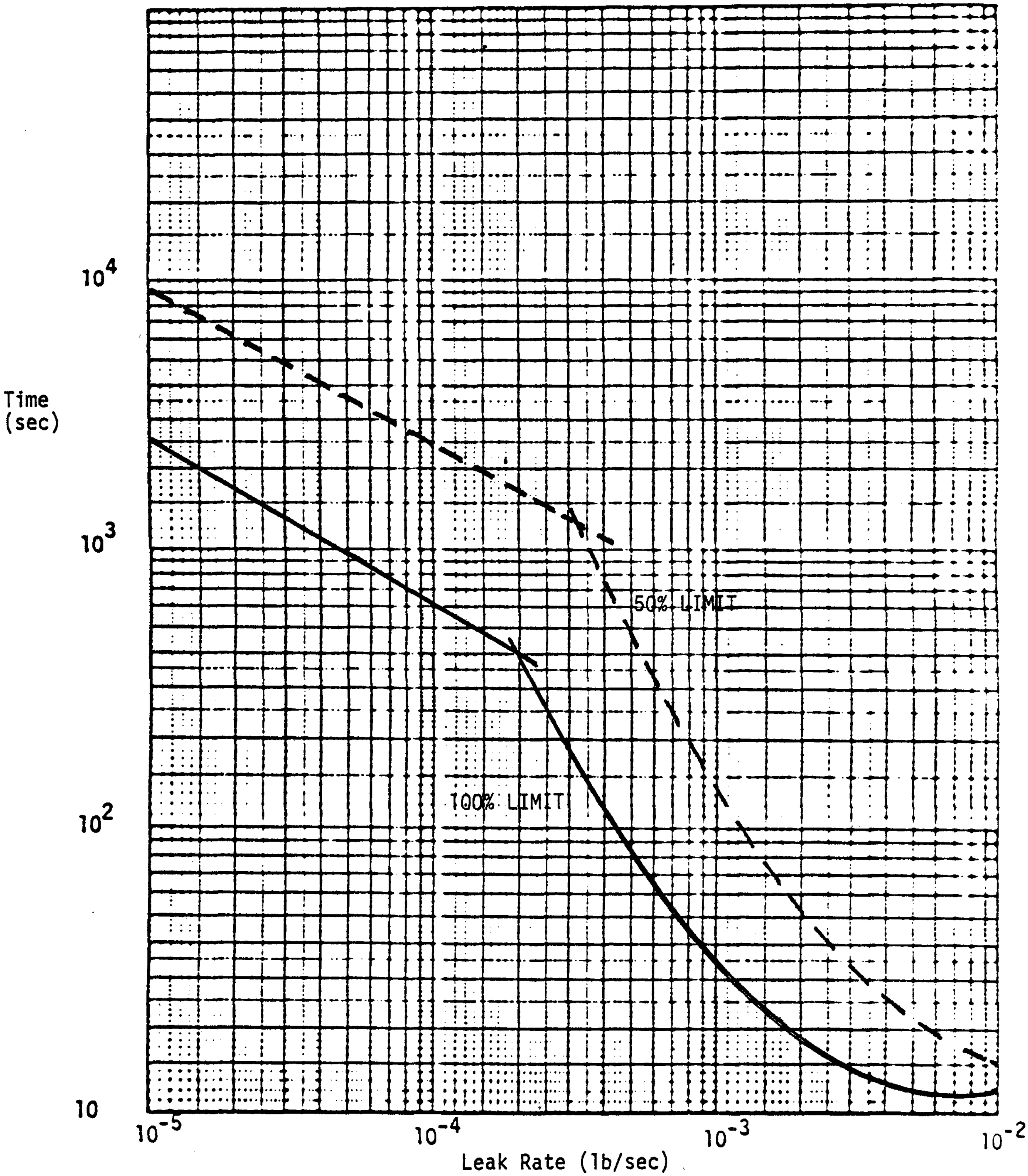



Figure 9. 900°F Wastage Limits for CRBRP Superheater, Main Body

be added 5 minutes for operator response (in the case of manual shutdown) and 30 seconds for blowdown. The minimum times for detection and safe shutdown are the sums of these times: 390 sec with manual shutdown and 90 sec with automatic shutdown. Inspection of the CRBRP wastage limit curves show that the maximum leak rates that can be protected against (i.e., no secondary failures) are as follows (using 100%-limit curves):

| Sodium Temperature (°F) | Maximum Leak Rate (lb/sec) | |
|---|---|---|
| | W/Manual Shutdown | W/Automatic Shutdown |
| 650 | $4.6 \times 10^{-4}$ | $1.7 \times 10^{-3}$ |
| 860 | $2.3 \times 10^{-4}$ | $5.4 \times 10^{-4}$ |
| 900 | $2.0 \times 10^{-4}$ | $4.8 \times 10^{-4}$ |

Clinch River System 53 initiates rapid blowdown and scram (e.g., SG-07U) at a leak rate of $6.5 \times 10^{-3}$ lb/sec. Judging by the above table, this value is high. It appears appropriate to consider rapid blowdown at a minimum leak rate of $2 \times 10^{-4}$ to $5 \times 10^{-4}$ lb/sec. The CRBRP leak protection curves (Figures 7-9) are reasonable approximations to those for the advanced steam generators; more accurate curves for each advanced unit can be found in Reference 7.

The use of automatic shutdown (blowdown and scram) can provide additional protection against secondary wastage damage as compared to manual shutdown, as it eliminates the time required for operator response. However, the probability of false alarms with such a system must be kept very low to avoid spurious shutdowns and decreased plant availability.

## 5.0 SUMMARY AND CONCLUSIONS

The major conclusions of this study are the following.

1. The creep-fatigue damage due to a blowdown transient is independent of the rate of water-side blowdown following isolation. The damage depends primarily upon plant system characteristics which set the rate of IHTS sodium cooldown after reactor scram and main pump trip.

2. The time delay between a small leak alarm and reactor scram should be considered as a tradeoff between (1) providing time to confirm the existence of the leak to a reasonable level of assurance and (2) the potential for secondary tube wastage damage.

3. In general, there appears to be no incentive to delay water-side blowdown following scram because the additional stress damage due to blowdown is insignificant and the potential for wastage damage should be eliminated as quickly as possible. One exception is the case of multiple evaporators feeding a superheater (as for CRBRP) where the isolation and blowdown of one evaporator shortly after scram can cause significant additional stress damage to the superheater upper tubesheet.

4. When initiated, the water-side blowdown process should be rapid. About 30 seconds blowdown time appears practical and adequate, based on the CRBRP design.

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# APPENDIX A. WASTAGE LIMITS

The pertinent wastage phenomena are of two types: (1) impingement wastage of a nearby tube and (2) self-wastage of the leaking tube. These are discussed separately below.

## A.1 Impingement Wastage

An extensive data base has been built up around the world for impingement wastage of 2-1/4 Cr-1 Mo steel at temperatures and tube spacings characteristic of the steam generator designs under consideration. The recommended correlation equations which have been used in this report are those of R. Anderson [5] of the UKAEA:

Steam Injection $$W = 2500 \exp - [0.255 (\ln 3.42\ M/L)^2 + 4114/T]$$

Water Injection $$W = 3.08 \exp - [0.6658 (\ln 0.72\ M/L^{1/2})^2]$$

where:

$W$ = wastage rate (mm/min)
$M$ = steam or water injection rate (gm/sec)
$L$ = leak to target spacing (mm)
$T$ = sodium temperature (°K)

These equations have been shown to correlate UKAEA, U.S., Japanese and German data well over a steam leak rate range of $1.8 \times 10^{-4}$ lb/sec ($8 \times 10^{-2}$ gm/sec) to 0.022 lb/sec (10 gm/sec) and a water leak rate range of $1.1 \times 10^{-3}$ lb/sec (0.5 gm/sec) to 0.13 lb/sec (60 gm/sec).

The CRBRP steam generator tube pattern is triangular spacing with a pitch of 1.125 inch. The tube O.D. is 0.625 inch and the wall thickness is 0.109 inch. 80% wastage penetration is assumed to result in tube failure. The minimum distance to an adjacent tube is 0.5 inches, and to a tube in the second row 1.324 inches. This difference in distance has a major effect on the rate of impingement wastage, as can be seen by inspection of the above equations.

If it is assumed that there is no preferred orientation for leaks, the bundle geometry results in 47% of leaks directed at an adjacent tube and 53% at a tube in the second row removed from the leaking tube. For the adjacent tube, no impingement damage can result if the leak is less than ∿2 mils diameter because the sodium-water reaction zone will not reach the adjacent tube. For a tube in the second circle, impingement damage will not result if the leak size is less than ∿5 mils. This is a direct consequence of the fact that experimental data show no impingement damage for L/D's (distance to target tube/leak hole diameter) greater than 300. Similarly, for any leak size greater than 2 mils, the impingement damage on the more distant tube will be less because of the correspondingly greater L/D.

The most rapid impingement wastage for leak rates up to $10^{-2}$ lb/sec is a direct (normal) impingement on an adjacent tube; this is plotted as the 100% wastage limit curves in Figures 7, 8, and 9. Since at least half ot the leaks will impinge on a second row tube, direct impingement on such a tube is plotted as the 50% limit curves in these figures (50% limit represents that one-half of the secondary tube failures will occur more rapidly and one half will occur slower.)

## A.2 Self-Wastage

The only available correlations for self-wastage are those of Gudahl and Magee [6]:

| | |
|---|---|
| Steam, 900°F (482°C) | $p = 49.4\ m^{0.61}$ |
| Steam, 860°F (460°C) | $p = 8.748\ m^{0.585}$ |
| Liquid or 2-Ø Mixture, 580 - 650°F (308 - 343°C) | $p = 0.667\ m^{0.5}$ |

where:

$p$ = effective penetration rate (mil/sec)
$m$ = injection rate (lb/sec)

The available U.S. data extend over the range of $7 \times 10^{-7}$ to $5 \times 10^{-4}$ lb/sec and are shown in Figures A1 and A2 reproduced from Reference 6.

The above self-wastage equations are maximum bounds on the penetration rate or, in other words, represent the minimum observed times to sudden enlargement. Thus, they are the 100% limit lines of Figures 7, 8 and 9. 50% limit lines were constructed as the mean (best fit curve) of the data at each sodium temperature level.

The sensitivity limit of the chemical detectors in the CRBRP geometry and operating conditions is about $2 \times 10^{-5}$ lb/sec. Leaks below this size cannot be detected. Given enough time, and if they do not permanently plug, these micro-leaks will enlarge to final rates in excess of $10^{-3}$ lb/sec. However, some time is required for them to "grow" through the detection range of $\sim 2 \times 10^{-5}$ to $\sim 10^{-3}$ lb/sec. The data of Reference 6 show this time to be in excess of 50 minutes at sodium temperatures of 650°F or less. Therefore, detection and safe shutdown will occur before enlargement is completed. At 860°F, the period of enlargement in the detection range (from $2 \times 10^{-5}$ to $10^{-3}$ lb/sec) was from 1 to 27 minutes. Approximately 40% of the leaks required more than 5 minutes for enlargement.

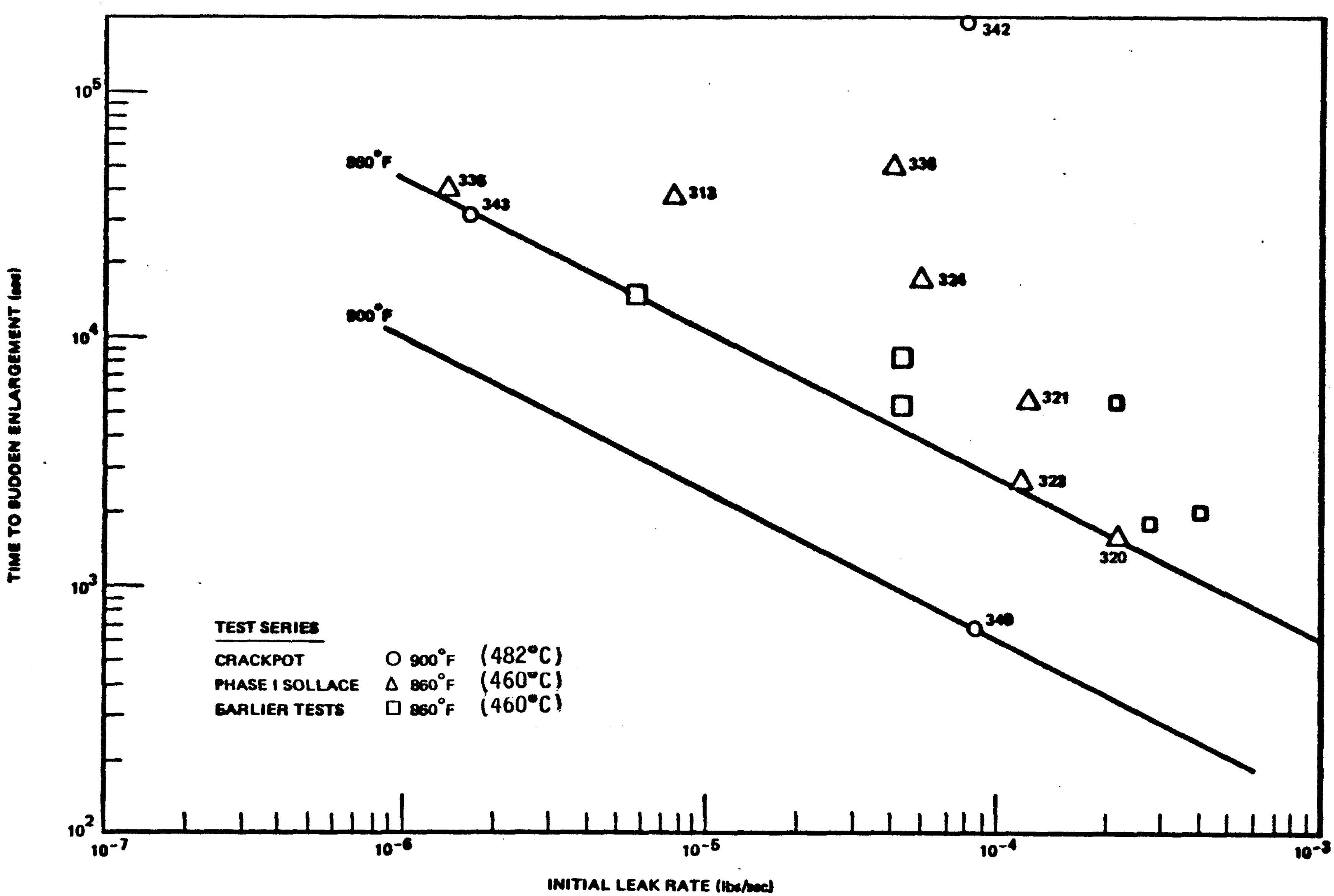


Figure A1. Self-Wastage Time to Sudden Enlargement (860 - 900°F)

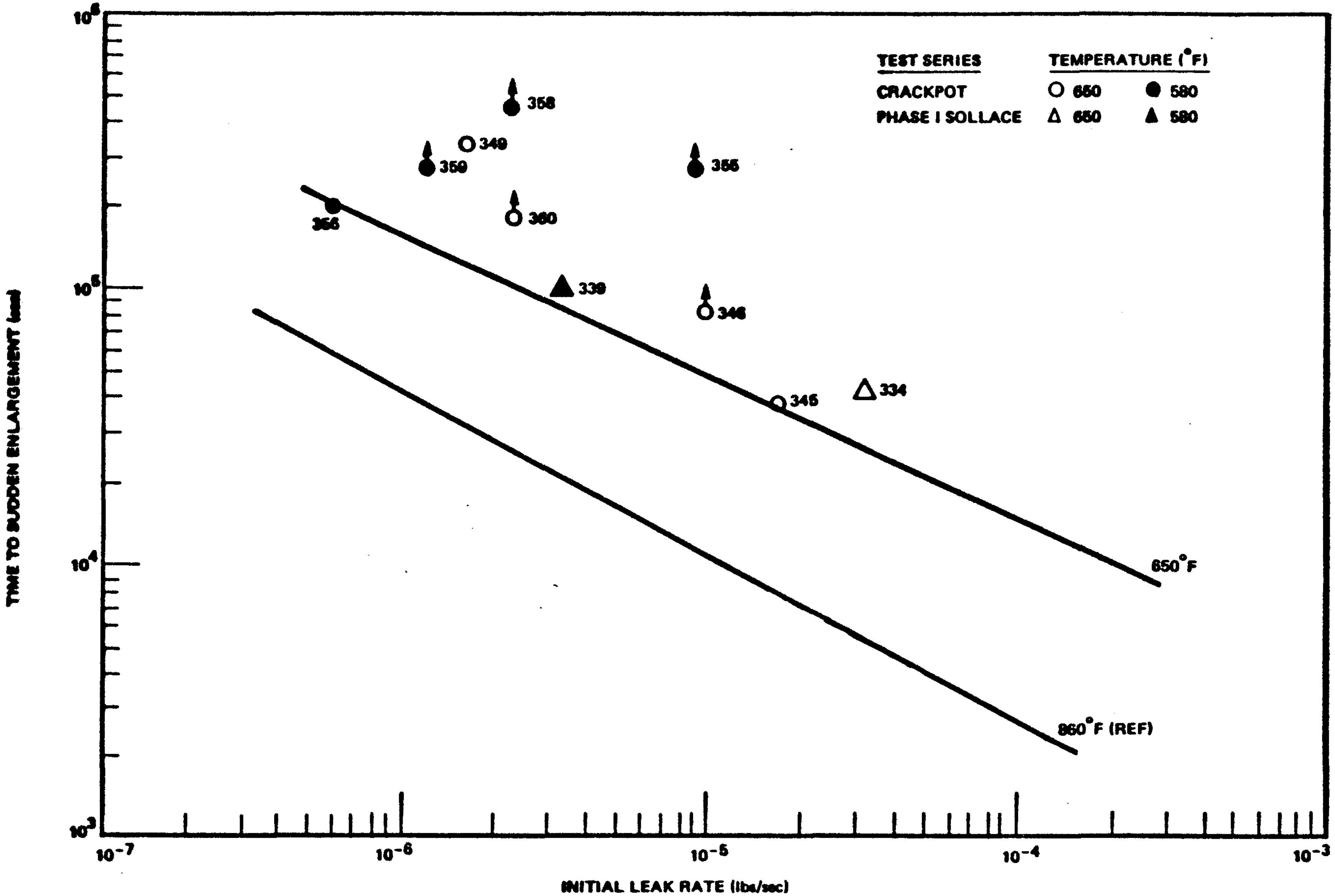


Figure A2. Self-Wastage Time to Sudden Enlargement (580 - 650°F)