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**ENERGY SYSTEMS AND
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ADVANCED REACTOR SYSTEMS DEPARTMENT

GENERAL ELECTRIC COMPANY . . . 310 DEGUIGNE DRIVE, P.O. BOX 508
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XL-791-10134

September 17, 1981

Mr. S. G. Harbison, Director
Nuclear and Magnetic Fusion Division
U. S. Department of Energy
San Francisco Operations Office
1333 Broadway
Oakland, California 94612

SUBJECT: DOE Contract No. DE-AT03-76SF70030, Work Package No. 15 40 10.1,
LMFBR Steam Generator Systems Development, WPT No. SG027,
Subtask X9, Automatic Leak Protection System

*Intermediate Leak Protection/Automatic Shutdown for B&W
Helical Coil Steam Generator*

REFERENCE: Letter, W. V. Leeburn to S. G. Harbison, "Advance Copy -
GEFR-00559, Intermediate Leak Detection and Automatic
Shutdown to Minimize LMFBR Steam Generator Damage Propa-
gation," XL-791-10058, dated April 30, 1981.

Dear Mr. Harbison:

The attached report on automatic shutdown is submitted in fulfillment
of Milestone X9.4 of SG027.

The report summarizes a follow-on study to the multi-tiered Intermediate
Leak/Automatic Shutdown System report referenced above. It makes the auto-
matic shutdown system specific to the Babcock and Wilcox (B&W) helical coil
steam generator and to the Large Development LMFBR PLant. Threshold leak
criteria specific to this steam generator design are developed, and perfor-
mance predictions are presented for a multi-tier intermediate leak, auto-
matic shutdown system applied to this unit. Preliminary performance predic-
tions for application to the helical coil steam generator were given in
the referenced report; for the most part, these predictions have been con-
firmed. The importance of including a cover gas hydrogen meter in this
unit is demonstrated by calculation of a response time one-fifth that
of an in-sodium meter at hot standby and refueling conditions.

Mr. S. G. Harbison

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XL-791-10134
September 17, 1981

Dr. P. M. Magee may be contacted regarding this transmittal.

Very truly yours,

A handwritten signature in cursive script, appearing to read "W. V. Leeburn".

W. V. Leeburn, Manager
Steam Generator Projects

Attachment

WVL/PMM/mj

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INTERMEDIATE LEAK PROTECTION/AUTOMATIC SHUTDOWN
FOR HELICAL COIL STEAM GENERATOR

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1. INTRODUCTION

1.1 Background

Previous evaluations [1,2] of steam generator automatic shutdown systems, reacting to a signal of an intermediate size water-to-sodium leak, have been based upon Clinch River Breeder Reactor Plant (CRBRP) geometry and operating conditions. Evaluations which focus on future plants/steam generators are needed to apply this approach to the Large Development Plant (LDP) and advanced steam generator concepts.

This report summarizes a short follow-on study to the multi-tiered Intermediate Leak/Automatic Shutdown System report [2] to make the shutdown system specific to the Babcock and Wilcox (B&W) helical coil steam generator and to the LDP to the extent that system information is available. Threshold leak criteria specific to this steam generator design are developed, and performance predictions are presented for a multi-tier intermediate leak, automatic shutdown system applied to the helical coil unit.

1.2 Scope of Study

The study consists of four parts, each of which is covered by a separate section of this report.

The threshold leak size is reconfirmed in Section 2. In Section 3, scenarios of tube wastage failure propagation within the B&W helical coil unit are developed. These are used to establish threshold leak criteria for shutdown; the criteria are compared to that developed previously for CRBRP. Section 4 summarizes the principal candidate leak detection systems in terms of performance as intermediate leak detectors relative to the threshold leak criteria. Performance predictions are given at 100% power, 40% power and hot standby conditions. Section 5 concludes the report with a discussion of the reference multi-tier system applied to the B&W helical coil steam generator.

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2. THRESHOLD LEAK SIZE

A detection/shutdown criterion was selected in the earlier studies [1,2] for the CRBRP steam generators to insure achievement of the automatic shutdown system design goals and to furnish a common basis for comparison of candidate leak protection methods: "The automatic shutdown system should detect, alarm and initiate blowdown within 20 seconds upon the first indication of a leak exceeding a threshold value of 0.01 lb/sec."

In translating this criterion to the helical coil geometry, two questions must be answered. Is the threshold leak rate of 0.01 lb/sec acceptable or must it be revised? Can the 20 seconds action time be relaxed? The former question is addressed in this section. The latter question will be investigated in Section 3.4 after leak propagation sequences are developed.

One wishes to select the threshold leak to be a very small secondary leak, a size that will be exceeded by essentially all secondary impingement leaks and all self-enlarged primary leaks. The rationale and data base for the 0.01 lb/sec selection for CRBRP are given in Ref. 2.

For the 0.01 lb/sec leak to be an acceptable threshold size for the helical coil unit, it is only necessary to show that secondary (and self-enlarged) leaks will be larger (or the same size) for the helical coil unit as for the CRBRP hockey stick unit. This is done by noting that the uniform CRBRP spacing between tubes is 0.595 inches, while the helical coil unit has variable spacing with minimum of 0.75 inch radially and 0.625 inch axially. Thus a given sized primary leak will result in a larger secondary impingement wastage hole in the hockey stick unit. (Reference 4 summarizes data obtained in the SONAR rig showing that the diameter of the secondary wastage hole increases as L/D_0 increases.)

The case for primary leaks enlarged by self-wastage is inconclusive. All data available in the literature are at or near the CRBRP wall thickness of 110 mils. However, it seems reasonable to assume that the effect

of wall thickness on going from 110 to 170 mils is negligible on the reaction process which "eats" its way back to the water-side and that the controlling orifice size, at the inside of the tube, will be the same in both cases.

It is concluded that the 0.01 lb/sec leak rate is a conservative threshold value, suitable for the B&W helical coil steam generator as well as for the CRBRP hockey stick units.

3. LEAK PROPAGATION SEQUENCES

3.1 Development of Scenarios

In order to provide a consistent basis to compare various candidate leak protection systems, several leak propagation scenarios for the CRBRP hockey stick steam generators were hypothesized in Ref. 2. The same assumptions have been used herein to develop similar scenarios for the helical coil unit. One sequence is selected so as to be the most rapid tube failure propagation and water addition sequence possible. A second sequence is developed to provide a realistic time delay between tube failures; this sequence will be referred to as "Slower Propagation".

Because of the difference in penetration rates and leakage rates for steam and water, different scenarios must be developed for high temperature conditions (typical of active region of steam generator at full power) and low temperature conditions (e.g., lower tubesheet at power, hot standby). Geometry and operating conditions for the B&W helical coil steam generator are taken from Appendix D of Ref. 3.

3.2 Leak Propagation at High Temperature

The CRBRP threshold leak of 0.01 lb/sec was first investigated. Analysis showed that this leak size was the worst case. That is, all leaks greater than 0.01 lb/sec (which would alarm) require somewhat longer times to produce secondary failures.

For the most rapid failure sequence, the initial 0.01 lb/sec leak is assumed to be aimed directly at an adjacent tube to give the most rapid failure. It will be noted that the spacing between tubes is not uniform in the helical coil unit. The worst spacing for wastage damage was found to be approximately 0.78 inches, corresponding to 30 L/D for a 0.01 lb/sec steam leak. Failure of the target tube is assumed to result in a second, larger sodium-water reaction jet again aimed to give maximum wastage rates on a nearby tube. The "Slower Propagation" scenario assumes that the initial leak is aimed off-center on the adjacent tube; one-half the direct impingement rate is used to account for the misaligned impingement. The hole drilled is assumed to be one-half the diameter expected as a result of direct impingement. Each additional failure is assumed to have similar orientation and penetration effects.

The results are summarized in Figure 1. (Detailed calculations are provided in Appendix A.) In the most rapid propagation cases, the second failure occurs in 20-28 seconds. The resulting secondary leak is about 6.6-8.2 lb/sec. (For the 1.25 inch OD helical coil tubing, one DEG is approximately 15 lb/sec of steam, as compared to 3.2 lb/sec for the smaller CRBRP tubing.) In the more realistic scenarios, the second failure occurs after 40-56 seconds. This second failure has a leak rate of 1.6-2.0 lb/sec.

3.3 Leak Propagation at Low Temperatures

Results for these conditions are summarized in Figure 2. (Detailed calculations are given in Appendix A.) Again, a threshold leak of 0.01 lb/sec was first investigated. However, it was found that somewhat larger leaks, on the order of 0.025 lb/sec liquid water, required less time to produce secondary failures. For the most rapid propagation cases, an initial leak of 0.01 lb/sec results in a ~6 lb/sec secondary leak in 97-136 sec and an initial leak of 0.025 lb/sec generates a secondary leak in ~31 sec. In the more realistic scenarios, the second failure occurs after 194-272 seconds for 0.01 lb/sec initial leak and ~62 seconds for a 0.025 lb/sec initial leak.

3.4 Comparison of Secondary Failure Times to CRBRP Values

The times required for the first secondary failure (following the threshold leak) are summarized in Table I and compared to corresponding values calculated for the CRBRP steam generators (from Ref. 2).

Table I
Minimum Times to Secondary Failure

	<u>Time (sec)</u>			
	<u>Helical Coil SG</u>		<u>CRBRP</u>	
	<u>Worst Case</u>	<u>Most Probable</u>	<u>Worst Case</u>	<u>Most Probable</u>
Power Operation	20-24	40-56	12	24
Hot Standby or Refueling	31	62	20	40

This table indicates that allowable times for alarm and shutdown are somewhat longer for the helical coil unit than for the CRBRP hockey stick units. The table also suggest some relief is possible in the definition of the threshold leak criterion, particularly at hot standby or refueling conditions.

It is recommended that, for the B&W helical coil unit, the threshold leak criterion be modified:

"The automatic shutdown system should detect, alarm and initiate blowdown upon the first indication of a leak exceeding a threshold value of 0.01 lb/sec within 30 seconds at power operation and 50 seconds at hot standby or refueling conditons".

4. CANDIDATE LEAK PROTECTION SYSTEMS

A number of possible leak protection systems were investigated in Ref. 2 for application to the CRBRP steam generators. In this follow-on study, the most promising have been explored further. Namely, a rapid response chemical detection system, low frequency acoustic detection and high frequency acoustic detection. It should also be noted that

preliminary predictions for the helical coil steam generators were made in Ref. 2; these have been reviewed and updated or corrected as necessary.

4.1 Rapid Response Chemical Leak Detection

It is envisioned that the B&W helical coil steam generator will be monitored by a rapid response, in-sodium H meter (or OH module) mounted on the sodium outlet pipe and by a cover gas H meter on the top of the vessel monitoring the cover gas space in the unit. Both types of meters are very sensitive to small water-to-sodium leaks and provide significantly greater sensitivity than the 0.01 lb/sec leak rate required by the criterion. (See, for example, Figures 17-20 of Ref. 3.) Performance limitations are set by the meter response time which is the sum of the sodium flow transport time plus the inherent delay times in the meter.

Maximum flow transport times through the steam generator are summarized in Table II. These are based on a total vessel length of 81.7 ft and an average sodium velocity of 2.5 ft/sec at full power. The response time of the in-sodium H-meter is the sum of this transport time and an inherent meter delay time of 16 seconds, as estimated by ANL [2].

Table II
Response Times for Chemical Detector
On Sodium Outlet Line

<u>Operating Condition</u>	<u>Max. Transport Time (sec)</u>	<u>Meter Delay Time (sec)</u>	<u>Total Response Time (sec)</u>
100% Power, Flow	34	16	50
40% Power, Flow	85	16	101
Hot Standby (7% Flow)	486	16	502

The cover gas meter is able to detect effectively any leaks in the cover gas region, including leaks at the four upper tubesheets which are in side cavities. The cover gas meter is also able to detect any hydrogen bubbles resulting from under-sodium leaks which reach the cover gas space.

This can occur in two ways: (1) bubbles rise in the steam generator against the downward sodium flow and (2) bubbles are carried around the entire IHTS loop and returned to the cover gas space. The latter case, obviously, does not give detection times as short as does the in-sodium meter on the outlet line.

The effectiveness of cover gas detection of under-sodium leaks is dependent on the relative rates of bubble rise and sodium flow. For hydrogen bubbles of 160 to 390 mils diameter, rise velocities are ~ 0.12 to 0.77 ft/sec at power conditions. At hot standby, rise velocities are 0.38 to 1.6 ft/sec for bubbles of 39 to 390 mils. The average sodium velocity in the unit is 2.5 ft/sec at 100% power, 1 ft/sec at 40% power and 0.18 ft/sec at hot standby. Thus, bubbles will not rise to the cover gas space under the 100% power condition and may not under the 40% power condition. Most of the hydrogen bubbles generated at hot standby are able to rise to the cover gas space. This is particularly true when one is considering leak rates of 0.005 to 0.01 lb/sec; large quantities of reaction products will be generated producing large, rapidly rising bubbles.

Assuming a minimum rise velocity of 1 ft/sec, the cover gas meter will respond to a leak at the bottom of the vessel under hot standby conditions within 100 sec. This is a significantly faster response than that of the in-sodium meter and demonstrates the importance of inclusion of a cover gas meter for the helical coil unit.

4.2 Low Frequency Acoustic Detection

The low frequency acoustic system utilizes multiple accelerometers mounted on the steam generator vessel. It detects and locates the leak by the acoustic "noise" produced in the 1-10 KHz frequency ratio. The critical parameter is the signal-to-noise ratio; that is, the ratio of the acoustic leak signal to the sum of the various background noises.

The calculations of Ref. 2 were checked for this study. The background noise estimates are correct, as is the calculation of the acoustic signal

for steam injections. Ref. 2 states that the "estimated" signal strength for liquid water injections is 1/3 that for steam injections or:

$$P (\mu\text{bar}) = 120 G(\text{gm/sec})^{0.8}$$

This equation has since been confirmed by tests in the SONAR rig [Ref. 5]. In conclusion, the system performance predictions given in Ref. 2 remain the best available estimates. These are summarized in Table III.

Table III. Performance Predictions for Low Frequency Acoustic System (Based on Min. S/N of 0.2)

Operating Condition	Background Noise (μbar)		Req. Signal Strength (μbar)		Min. Detectable Leak Rate (lb/sec)	
	At Sodium Surface	At LTS	At Na Surface	At LTS	At Na Surface	At LTS
100% Power	3724	66	745	13.2	$5.5 \times 10^{-3*}$	1.4×10^{-4}
40% Power	93	24	19	4.8	5.4×10^{-5}	3.9×10^{-5}
Hot Standby or Refueling	24	24	4.8	4.8	3.9×10^{-5}	3.9×10^{-5}

*For steam injection, others are assumed to be water injection

In all cases, the acoustic system meets the criterion; the given maximum leak sizes can be detected reliably in 20 sec or less. The capability of the low frequency acoustic leak detection system to function as a small leak ($< 10^{-3}$ lb/sec) detector at low power and standby conditions should also be noted.

4.3 High Frequency Acoustic Leak Detection

The high frequency acoustic leak detection system uses noise emission sensors (~ 300 KHz range) mounted on wave-guides off the steam generator tubesheets. The heat transfer tubes are employed to transmit the leak signal to the nearest tubesheet and then across the tubesheet to the sensors. The critical parameters are the signal-to-background noise ratio and the attenuation along the tubes.

The calculations of Ref. 2 were confirmed. Performance predictions are summarized in Table IV. In each case, the leak is assumed to be at the center of the unit. Leaks closer to either tubesheet will produce stronger signals resulting in smaller detectable leak rates.

Table IV. Performance Predictions for High Frequency Acoustic System (Based on S/N of +5dB)

Operating Condition	Total Length, TS to TS(H)	Max. Att. to TS(dB)	Max. Req. Signal Strength(dB)	Min. Detectable Leak Rate (lb/sec)
Power	300*	73.8	-20.0	0.069
Hot Standby or Refueling	300*	73.8	-18.0	0.051

*Total coil length

Without modifications, the high frequency acoustic system does not meet the criterion for this unit as it requires a minimum leak of 0.07 lb/sec. This is a direct consequence of attenuation along the long length of coiled heat transfer tubing. The system is certainly effective near the tubesheets. It can also be supplemented by a ring(s) of sensors mounted in the central region of the vessel wall. Detection times will be within 20 seconds.

4.4 Temperature Rise in Sodium Flow Segment

It has been suggested that, since the sodium flow in the helical coil unit is channeled into 12 segments with essentially no mixing between segments, sodium temperature rise could possibly be used as an early indication of an intermediate leak. Calculations have been made which show this to be impractical; these are summarized below.

The energy addition from a sodium-water reaction is 1230 Btu/lb sodium reacted, or 1580 Btu/lb water reacted. Assuming that each of the 12 flow segments is totally separate and carries 1/12 the total sodium

flow of 4525 lb/sec at 100% power, the sodium temperature rise within the segment due to a threshold leak of 0.01 lb/sec is:

$$\Delta T = \frac{E}{WC_p} = \frac{1580(0.01)}{\frac{4525}{12} (0.3)} = 0.14^\circ\text{F}$$

This is undetectable. To have any chance of detecting a sodium temperature rise due to a sodium-water reaction, one would have to consider leaks in the range of 1 lb/sec (e.g., $\Delta T = 14^\circ\text{F}$ for 1 lb/sec water injection/reaction).

4.5 Other Candidate Leak Detection Methods

Other methods of detecting water-to-sodium leaks in the range of 0.01 lb/sec do not appear promising when applied to the Large Development Plant and the B&W helical coil steam generator.

Ultrasonic gas-phase sensors were suggested as a possible leak detection method in Ref. 2. However, for the application under consideration, they appear to offer no advantages over chemical leak detection methods (and have several disadvantages). A gas-phase sensor on the sodium outlet line would have response times which, at best, would be only slightly less than those for the rapid response H-meter; flow transport times would be identical. The prime interest in gas-phase detectors has been for low temperature, low flow conditions where a gas-phase detector would be mounted at the top of the steam generator to monitor the presence of bubbles. The basic helical coil steam generator, unlike other designs, include a cover gas space and provision for a cover gas H-meter. Such an arrangement is much more effective than use of an ultrasonic gas-phase detector.

Other proposed leak detection methods relate to sensing changes in variables associated with the IHTS expansion tank, such as sodium-level change, inlet line velocity, etc. These were found to be ineffective for the CRBRP loops. For LDP which will have IHTS loops 2 1/2 to 3 times

the size of the CRBRP loops, the sensitivity of such devices to steam generator leaks is further degraded.

5. MULTI-TIER SYSTEM

The reference multi-tier system consists of the two acoustic systems and the rapid response chemical system. The estimated response capabilities, when applied to the B&W helical coil steam generator operating in the Large Development Plant, are given in Table V.

Table V
Performance Capabilities of Multi-Tier System

	Minimum Leak Size for Automatic Shutdown		
	100% Power	40% Power	Hot Standby
<u>Individual Subsystem</u>			
Chemical	5×10^{-3} lb/sec in 50s	5×10^{-3} lb/sec in 100s	5×10^{-3} lb/sec in 100s
Low Freq. Acoustic	6×10^{-3} lb/sec in 20s	5×10^{-3} lb/sec in 20s	5×10^{-3} lb/sec in 20s
High Freq. Acoustic	0.07 lb/sec in 20s	0.07 lb/sec in 20s	0.05 lb/sec in 20s
<u>Combination of Subsystems</u>			
Chem + LFA	6×10^{-3} lb/sec in 50s	5×10^{-3} lb/sec in 100s	5×10^{-3} lb/sec in 100s
Chem + HFA	0.07 lb/sec in 50s	0.07 lb/sec in 100s	0.05 lb/sec in 100s
LFA + HFA	0.07 lb/sec in 20s	0.07 lb/sec in 20s	0.05 lb/sec in 20s

Note that alarm levels less than 0.005 lb/sec are not recommended although the calculations of Sections 4.2 and 4.3 indicate that smaller leaks can be rapidly detected under some operating conditions. The limit of 0.005 lb/sec is used to preclude the possibility of false alarms.

It is recommended that the chemical system (and possibly the low frequency acoustic system, because of its sensitivity at low power conditions) also function as a small leak protection system with operator intervention. This will provide significant additional protection for leaks from 10^{-5} to 2×10^{-3} lb/sec.

REFERENCES

1. Letter, W. V. Leeburn to S. G. Harbison, "Effectiveness of Various Leak Protection Systems as Initiators of Automatic Shutdown", XL-791-00115, dated August 27, 1980.
2. P. M. Magee, "Intermediate Leak Detection and Automatic Shutdown to Minimize LMFBR Steam Generator Damage Propagation", GEFR-00559, April 1981.
3. P. M. Magee, et al., "Assessment of Candidate Leak Detection Systems Against Requirements for Post-CRBRP Steam Generators", GEFR-00476, August 1979.
4. Ko Chen, "Final Leak Sizing for LLTR Series II Test A-3 and Results from Supporting Tests in the SONAR Rig," Attachment to GE letter XL-796-00046, March 1980.
5. Letter, W. V. Leeburn to S. G. Harbison, "Sodium-Water Reaction Acoustic Noise for Liquid Phase Injections," XL-791-10020, dated February 26, 1981.

COMPUTATION/RECORD SHEET

Prepared By: <u>P. Magee</u>	GENERAL ELECTRIC COMPANY Fast Breeder Reactor Department	Page No: <u>A.1</u>
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APPENDIX A - WASTAGE SCENARIOS FOR HELICAL COIL UNIT

Use calc methods of GEF2-00559, App A

Tube Bundle Geometry: Tube OD = 1.25 in thk = 0.170 in

Min Spacing = 0.625 - 0.75 in

① Low Temp (500-600°F) Conditions

a) Most Rapid Propagation

Threshold leak of 0.01 lb/sec water ~ 13 mil dia hole

$$\text{Impingement on 1st row tube} - \frac{L}{D} = \frac{625 - 750}{13} = 48 - 58$$

Corresponding Rate = 1.4 - 1.0 mil/sec

Wastage rate on 2nd row will be slower Continue with 1st row calc.

$$\text{Time to penetrate 80% of wall thk} = \frac{136}{1.4 - 1.0} = 97 - 136 \text{ sec}$$

$$\text{Size of hole drilled: } \frac{L}{R} = \frac{2L}{D} = 96 - 116 \quad D_w/D_o = 24$$

$$D_w = 24 (.013) = 0.312 \text{ inch} \quad W = 6.37 \text{ lb/sec liquid water}$$

This jet can reach another tube. Can get rate of ~ 2 mil/sec

$$\text{Time to penetrate 80% of wall thk} = \frac{136}{2} = 68 \text{ sec (additional)}$$

Note, however, 0.01 lb/sec initial leak is not worst case.

Worst case is at $L/D = 30$ with pen. rate of 4.4 mil/sec

$$\text{Hole size (Worst)} \quad D = \frac{L}{40} = \frac{625 - 750}{30} = .021 - .025 \text{ in}$$

∴ Worst case is initial leak of 0.024 - 0.035 lb/sec liq. water

$$\text{These will penetrate next tube in } \frac{136}{4.4} = 31 \text{ sec.}$$

Take second failure as occurring in 68 sec additional

b) Slower Propagation

Look at 0.01 lb/sec & 0.025 lb/sec liquid water initial injections

$$0.01 \text{ lb/sec: Time to penetrate 1st tube} = 2(97 - 136) = 194 \text{ to } 272 \text{ sec}$$

$$\text{Size of hole drilled: } D_w = \frac{1}{2} (.312) = .156 \text{ in} \quad W = 1.6 \text{ lb/sec}$$

Next tube in 2(68) = 136 sec additional

size of this hole & rate sufficient to rupture disc? yes

$$\frac{L}{D} = \frac{1.5}{.156} = 10 \quad D_w = \frac{D}{2} (.156) = .078$$

$$0.025 \text{ lb/sec: Time to penetrate 1st tube} = 2(31) = 62 \text{ sec}$$

$$W = 1.6 \text{ lb/sec.}$$

Second failure in 136 sec additional

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② High Temperature Conditions

a) Most Rapid Propagation

Threshold leak of 0.01 lb/sec steam ~ 26 mil dia hole

Impingement on 1st Row tube $\frac{L}{D} = \frac{625 - 78}{26} = 24 \text{ to } 25$

Corresponding Rate = 4.8 - 6.7 mil/sec

Impingement on 2nd Row tube will be somewhat slower.

Time to penetrate 80% of 1st Row tube wall thk = $\frac{136}{4.8 - 6.7} = 28 \text{ to } 20 \text{ sec}$

Size of hole drilled $\frac{D_w}{D_o} = 22 - 25 \quad D_w = 0.572 \text{ to } 0.650 \text{ in}$

$W_{\text{steam}} = 6.6 \text{ to } 8.5 \text{ lb/sec steam}$

On to next tube, fastest impingement rate is 6.7 mil/sec so takes minimum of 19 sec additional to fail tube. More reasonable rate for second failure would be $\frac{6.7}{2} = 3.35 \text{ mil/sec} \rightarrow 40 \text{ sec failure time}$.

Is 0.01 lb/sec worst case? YES

worst at $L/D = 32$ or $D = 0.021 - 0.025$ time is 19 sec min

Therefore, 0.01 lb/sec is worst case for steam. Larger leak rates require greater D and smaller L/D (less than 30).

b) Slower Propagation with 0.01 lb/sec steam threshold leak

Time to penetrate 1st Row tube = $2(20 \text{ to } 28) = 40 \text{ to } 56 \text{ sec.}$

Hole drilled $D_w = \frac{1}{2}(.572 \text{ to } .650) = .286 \text{ to } .325 \text{ inch}$

$W = 1.65 - 2.13 \text{ lb/sec steam}$

Next tube will fail in ~ 40 sec additional (min)
to ~ 80 sec (average)

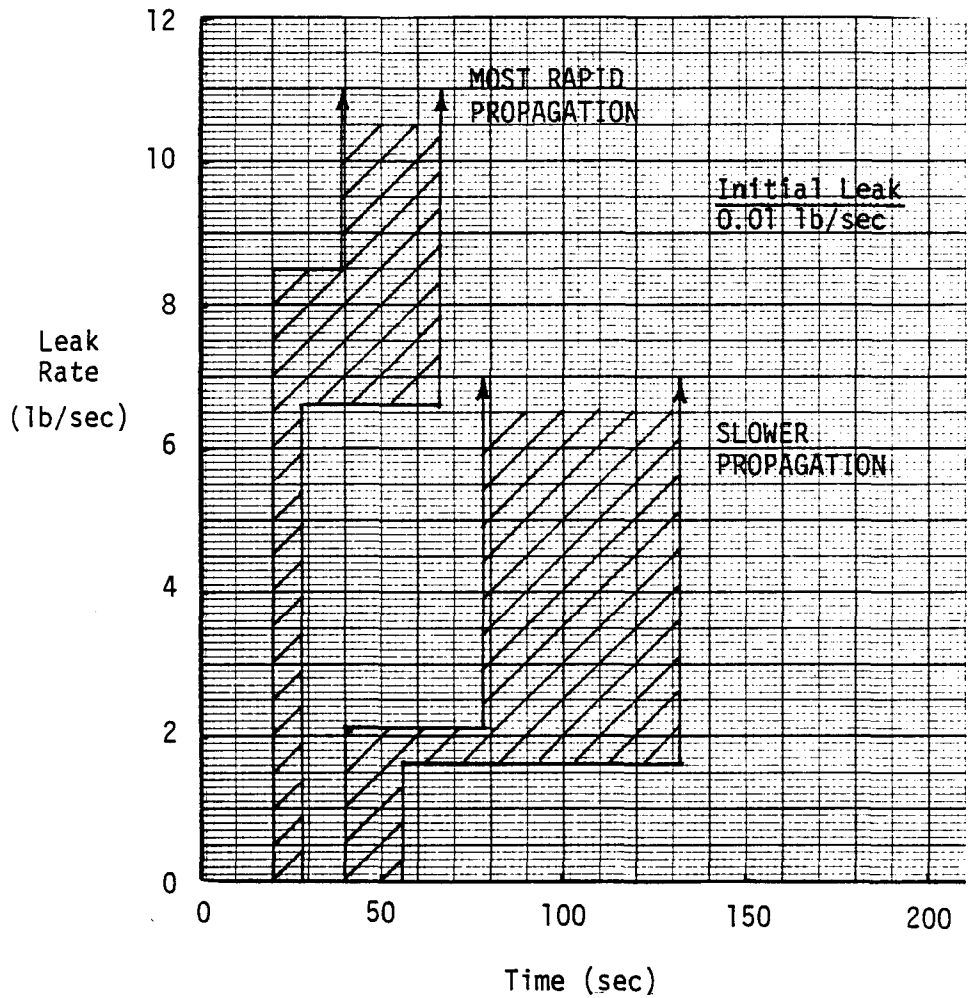


FIGURE 1

WASTAGE PROPAGATION AT HIGH TEMPERATURE
IN HELICAL COIL STEAM GENERATOR

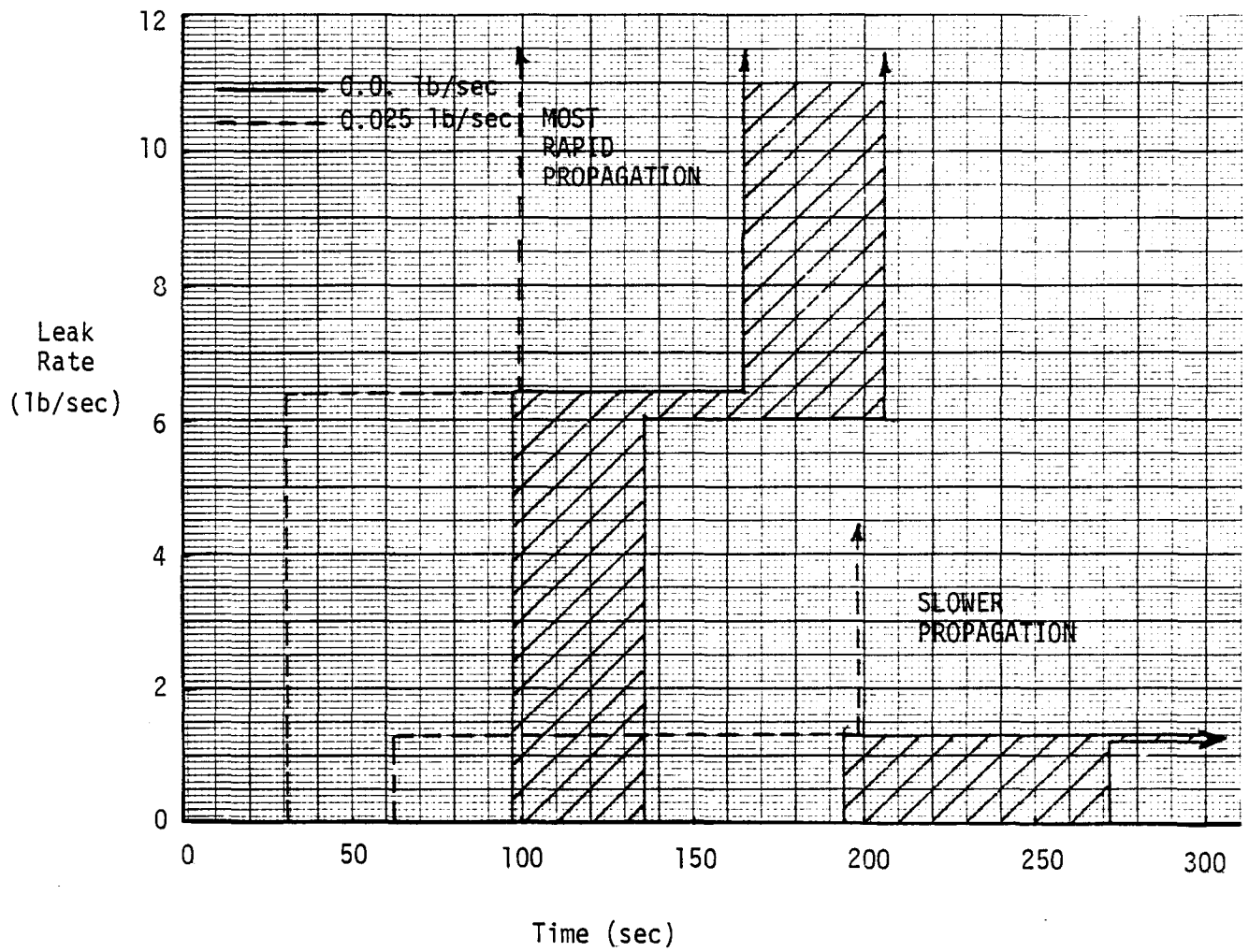


FIGURE 2
 WASTAGE PROPAGATION AT LOW TEMPERATURE
 IN HELICAL COIL STEAM GENERATOR