Tests and Analysis on Steam Generator Tube Failure Propagation

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Abstract

The understanding of leak enlargement and failure propagation behavior is essential to select a design basis leak (DBL) of LMFBR steam generators. Therefore, various series of experiments, such as self-enlargement tests, target wastage tests, failure propagation tests were conducted in a wide range of leak using test facilities of SWAT at PNC/OEC. Especially, in the large leak tests, potential of overheating failure was investigated under a prototypical steam cooling condition inside target tubes. In the small leak, the difference of wastage resistivity was clarified among several tube materials such as 9-chrome steels. In regard to an analytical approach, a computer code LEAP (Leak Enlargement and Propagation) was developed on the basis of all of these experimental results. The code was used to validate the previously selected DBL of the prototype reactor, Monju, steam generator. This approach proved to be successful in spite of somewhat over-conservatism in the analysis. Moreover, LEAP clarified the effectiveness of a rapid steam dump and an enhanced leak detection system. The code improvement toward a realistic analysis is desired, however, to lessen the DBL for a future large plant and then the re-evaluation of the experimental data such as the size of secondary failure is under way.

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1. Introduction[1)]

In an LMFBR steam generator, the prevention of a sodium-water reaction incident is very essential to maintain plant reliability even though it has no potential of jeopardizing the boundary of the primary heat transport system. To enhance the plant reliability, information of a water leak and its development behavior is needed. The study on tube failure propagation has been conducted for years at PNC/OEC. Objectives of our study are to clarify mechanisms of the failure propagation, to develop an analytical method for predicting the phenomena, and to validate the conservatism of design basis leak (DBL) of LMFBR steam generators .

Growth behavior of a sodium-water reaction can generally be described as follows: A water leakage into sodium initiates as a micro-leak due to faulty weld or other imperfection, and then self-enlargement of the leak hole would increase the water leak rate to a small leak or an intermediate leak range. The steam jet from the enlarged hole would impinge surrounding tubes and finally fail their integrity by wastage. Therefore, unless any countermeasure were taken against the leak, it might develop to a large leak level by sequential failure propagations. In the large leak, not only wastage but overheating, thrust load, etc. should be taken into consideration as mechanisms of the failure propagation.

In an actual plant system, however, a leak is detected by water leak detectors such as hydrogen monitors and then countermeasure operations including the closing of shut-off valves and an emergency water dump are taken. Then, the leak will terminate at an early stage as a micro-leak or a small leak before the sequential failure propagations occur.

A variety of leak development scenarios should be taken into account beside the above one. Some leaks may start from a small leak level without experiencing the micro-leak for example in the case that fluid vibration initiates the leak. Other mechanisms such as pipe-whipping are also considerable. After having considered all the mechanisms, however, wastage and overheating were thought to be the main contributors to the failure propagation. Thus, the R&Ds described here are focused on these two major failure mechanisms.

2. Experimental Studies on Failure Propagation

A primary objective of the failure propagation studies of Japan in 1970s was to provide sufficient data to validate the DBL of Monju steam generators. The studies consist of several series of experiments such as self-evolution tests, target wastage tests, failure propagation tests, and overheating tests by use of SWAT-1 through -4 test facilities. In the tests, 2-1/4Cr-1Mo steel was used as a tube material in accordance with the Monju specification. However, since 9Cr steels, especially modified 9Cr-1Mo steel, become preferable for the tube materials of a future larger plant after Monju, similar experiments were conducted in some leak ranges by changing test piece materials for 9Cr steels.

2.1 Self-Enlargement in Micro-Leak

A micro-leak study is aiming at determining a self-wastage rate and an enlargement ratio of the leak hole, which are expressed as a tube wall thickness divided by the period required for self-enlargement and a ratio of a new diameter after enlargement to an initial one, respectively. In the SWAT-4 tests, JIS-SUS304, JIS-SUS321, 2-1/4Cr-1Mo steel, 9Cr steels, and alloy-800 were used as the test piece materials. The comparison of the self-wastage rate among these tube materials indicates that the austenitic stainless steel JIS-SUS321 is more resistant against self-wastage than the 2-1/4Cr-1Mo ferritic steel but the mod. 9Cr-1Mo steel is most resistant among three.

One of the most important modification in the new test series is the adoption of a new manufacturing method of initial micro-defects. Though the micro-defect had been conventionally made by swaging a drilled circular hole, it was generated from a fatigue crack in a new series tests of 9Cr steels because the latter one was more realistic. Both types of micro-leak nozzles are shown in Figure 1. The swaged type nozzle were also used in the new tests to clarify the effect of the nozzle type on the self-enlargement behavior. The fatigue crack nozzle develops slightly faster than the swaged type one. More important feature is that the fatigue crack type nozzles are unlikely to plug during the experiment even at a low leak range below 10^{-4} (g/sec). This different plugging behavior seems to be related to the fact that the length/width ratios of the fatigue cracks are generally much larger than those of the swaged ones. Because the fatigue crack nozzle is thought to be more realistic than swaged one, the result of the fatigue crack tests is recommended to use in a self-enlargement evaluation.

2.2 Target Wastage in Small Leak2)

In the small leak range, wastage rates for various tube materials were measured using SWAT-2. Figure 2 compares the wastage rate as a function of a water leak rate among the 2-1/4Cr-1Mo steel, austenitic stainless steel (JIS-SUS321), and 9Cr steels. The 9Cr steels are situated in the middle of two conventional materials and are about two times as wastage-resistant as the 2-1/4Cr-1Mo steel. No significant difference, however, was observed among three types of 9Cr steels, i.e. mod. 9Cr-1Mo, 9Cr-1Mo-Nb-V, and 9Cr-2Mo.

2.3 Multi-tube Wastage in Intermediate Leak

In the intermediate leak range, plural tubes surrounding the leaking tube are wasted simultaneously. The internals consisting of about twenty test tubes were assembled and used to simulate the multi-tube wastage in SWAT-1 tests. In the early stage, the test tube material was a 2-1/4Cr-1Mo steel and target tubes were pressurized with nitrogen gas to detect a failure time. Although the cooling effect to be expected under a realistic condition was not taken into account then, a further prototypical condition is selected in the tests for mod. 9Cr-1Mo steel which are ongoing now. The comparison between the two conditions indicates that the sizes of holes under the cooling conditions are smaller than those without cooling.

2.4 Overheating Failure in Large Leak

In the large leak, the wastage is no more a predominant mechanism to cause failure propagation because the reaction zone does not exist stably due to a dynamic hydrogen generation. Instead, the potential of overheating failure seems to increase because reaction heat increases the tube wall temperature in a very wide area. The most severe points in the overheating failure would be potential of the large number of failing tubes and the short time for failure. Then it is very important whether the overheating failure could occur under prototypical conditions. Run 16 of SWAT-3 was carried out at the initial leak rate of 2.2 kg/sec. and a water-filled tube and twenty-four gas-filled tubes burst due to overheating. To confirm the overheating effect, a similar test was re-executed in Run 19 using water-flowing tubes instead of the water filled tubes. The tube configuration and the results were shown in Figure 3. No water flowing tubes in Run 19 burst at all and then it was demonstrated that the cooling effect of flowing water inside tube should not be ignored in the evaluation of the overheating failure.

Heat transfer coefficients at tube outer wall surface were obtained in the same series of the tests. Temperatures were measured by embedded thermocouples in the inner/outer wall of target tubes and a thermocouple placed in the reaction zone. The heat transfer coefficients were calculated with the numerical inversion of Laplace transform using the temperature data. Average heat transfer coefficients thus calculated ranges 8,000 - 10,000 (kcal/(m^2°Chr)) at the leak rate of 1 - 2 kg/sec, where 1 (kcal/(m^2°Chr)) is 1.16 (Watt/(m^{2}secK)). The coefficients are somewhat correlative with the leak size. That is, when the leak was relatively small and the jet was localized, the peak value was larger than 10,000 (kcal/(m^2°Chr)). On the other hand, when the leak is large enough to surround the tube entirely, it is lower than 8,000 (kcal/(m^2°Chr)). Figure 4 shows an example of a heat flux and a heat transfer coefficient in SWAT3 Run 19, where gas-filled tubes without cooling burst due to overheating. However, according to a simple thermal calculation, if a heat transfer coefficient on tube inside is as large as 5,000 (kcal/(m^2°Chr)), the tube can maintain the integrity. This number is realistic even under a steam flowing condition. From such an evaluation, it is concluded that the water/steam flow is so effective in the large leak that the overheating failure would not occur under actual plant conditions.

2.5 Sequential Failure Propagation

In addition to individual tests where only one step of leak development was simulated as described so far, almost full sequence failure propagation tests were conducted by use of SWAT-3. In Runs 14 and 15, a leak was initiated from a small leak and after several steps of failure propagation, the leak developed to a large leak or a larger intermediate leak. After the simulation of an emergency blow-down by depressurizing a water heater tank, the leak development and finally the sodium-water reaction were terminated. Failure propagation profiles of SWAT-3 Run 14 are illustrated in Figure 5.

3. Analytical Approach on Failure Propagation

3.1 Development of LEAP

A computer code LEAP (Leak Enlargement and Propagation) was developed to evaluate the failure propagation. It can simulate the failure propagation processes from the initiation of micro-leak, through a leak enlargement and propagation, a leak detection, and a steam dump, to the termination of the reaction, and provide a water leak rate fluctuation during the the leak progression. A flow diagram of the failure propagation and other relevant actions is outlined in Figure 6.

1) Initial conditions

In the calculation, firstly the following data should be input as initial conditions:

Tube data:	diameter, thickness, material, location
Steam conditions:	pressure, enthalpy, at initial stage and blow-down
Initial leak:	leaking tube, circumferential direction, hole diameter

2) Leak development

Under the above conditions, times required to cause self-enlargement and secondary failure are calculated respectively. If the time of the self-enlargement is shorter than that of the secondary failure, the leak hole diameter is changed for a new bigger one. In the opposite case, the most wasted point of one of the surrounding tubes has an opening as a secondary failure. The self-enlargement time, the secondary failure time, an enlargement factor, and the size of the opening are calculated using empirical formulas which are expressed with sufficient conservatism by a function of the initial leak rate mainly. The similar calculation continues for the secondary leak, tertiary leak, and so forth.

3) Leak detection

Detection times with various leak detectors can be calculated in the code. For example, a detection time with hydrogenmeters or acoustic detectors is provided as a function of a total leak rate. To provide the detection times with a cover gas pressure gauze and a rupture disk burst signal, a pressure build-up in a cover gas region of the steam generator is calculated considering the amount of generating hydrogen and a gas released through a gas line. Some calculations were made out of the above-mentioned ones in accordance with given assumptions and the fastest signal is adopted to shut down the system.

4) Blow down analysis

A depressurizing curve during a water/steam blow-down was analyzed separately using a blow-down code such as RELAP4 and provided to LEAP as a table. After the leak detection, blow-down is initiated and a water leak rate begins to decrease. When depressurizing a water/steam line is completed and the water is exchanged for an inert gas, the calculation is terminated.

3.2 Validation by SWAT-3 Data

Runs 14 and 15 in SWAT-3 are fully sequential simulation tests. That is, all of fifty-six tubes were filled with water at 150 ata (15 MPa), and the water injection was stopped after depressuring the water supply tank so as to simulate the blow-down during a sodium-water reaction accident in the actual steam generator system. A comparison between the time history of the Run 14 test result and that of LEAP calculation is shown in Figure 7. As shown clearly, the calculation always provides conservative values for both time and size of the failures. The maximum water leak rates of the test and analysis are 900 and 2,900 g/sec, respectively.

From the comparison above, it is concluded that though the present LEAP code cannot exactly identify the failed tube and the jet direction after a few stages of propagation, it can conservatively predict the total leak size and the timings of the individual tube failures for the analysis of the actual plants.

From an opposite point of view, however, it is clear that LEAP has over-conservatism in its leak scale evaluation. A primary reason is the conservatism of the empirical formula that provides the size of the secondary failure in the code. To improve the code for more realistic prediction, the re-evaluation of the experimental data and another series of tests are under way.

4. Application Analysis by LEAP

4.1 Analysis for Selecting Monju DBL

An objective of LEAP application to a Monju analysis is to validate the DBL of the present design including relevant equipments. Hence, as a whole, conservative parameters as shown in Table 1 were selected as a reference case of the validation calculation. For example, it was postulated that hydrogenmeters or pressure transducers in cover gas had no credit and only a rupture disk burst signal could be used as a leak detector. A water pressure decrease during a blow-down was calculated by the RELAP code. The result of the Monju application is shown in Figure 8. In spite of many conservative assumptions used in the calculation, the result of the LEAP calculation does not exceed the previously determined Monju DBL.

During the sensitivity study for Monju application, LEAP indicated that a leak detection system and a water/steam blow-down system with a quick response were so effective as to decrease the DBL. Thus, to develop a reliable quick detection system such as an acoustic detector can assure 1-DEG of DBL.

4.2 Post-Incident Analysis of PFR[3),4)]

Concerning the PFR incident, several investigations were conducted by UKAEA. Based on their studies, our view on the cause why the incident developed so large in PFR is summarized as below:

1) The existence of sodium leak flow from a center pipe caused the tube vibration and fretting. In general, the damage by this cause cannot be limited to a single tube.

2) The lack of emergency water blow-down system in the SH developed the failure propagation because the heating of water in almost closed system leads to failure of a large number of tubes in any way whether IGA was influential or not.

There are some other reasons such as the tube support structure and the leak detection system as stated by UKAEA, but the two reasons described above are most essential.

The LEAP code is not directly applicable to the PFR incident because the leak development scenario is thought to be rather specific to the PFR incident. Therefore, a kind of manipulation was necessary to apply LEAP to PFR. For example, a smaller value was input as initial wall thickness so as to simulate the wall thickness of the innermost tubes thinned by fretting before the incident. The analysis is under way.

5. Conclusion

Studies on the leak development have been conducted at PNC by use of the SWAT test facilities and the LEAP code to assess the design basis leak of FBR steam generators and to validate the safety design. The studies are concluded as follows:

1) More prototypical initial defect to simulate a micro-defect was manufactured with the fatigue cracking technique. Leak enlargement behavior of the new type nozzle was different from that of the conventional swaged nozzle.
2) In the micro-leak and small leak ranges, 9Cr steels are more resistant against the wastage than the 2-1/4Cr-1Mo steel which was representative ferritic steel as tube materials.
3) The consideration of cooling effect of tube internal surface is important to evaluate the failure propagation phenomena, especially on the size of secondary failure.
4) The prototypical large leak experiment and the heat transfer measurement indicated that the potential of overheating failure was low.
5) LEAP has a capability to evaluate DBL with conservatism in comparison with the SWAT-3 failure propagation tests.
6) The Monju DBL was validated with sufficient conservatism.
7) The R&D to improve LEAP more realistically is still under way.

REFERENCES

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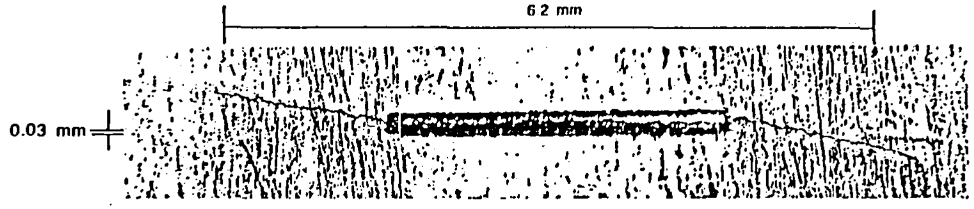
Table 1 Referential Assumptions on Monju Analysis

items	selections
steam generator	evaporator
leak site location	upper helical region
operational condition	full power
leak detection system	rupture disk burst signal
water/steam dump	emergency blow-down

Swaged type (x 50)



Fatigue crack type (x 25.7)

Figure 1 Test pieces of swaged type and fatigue crack type

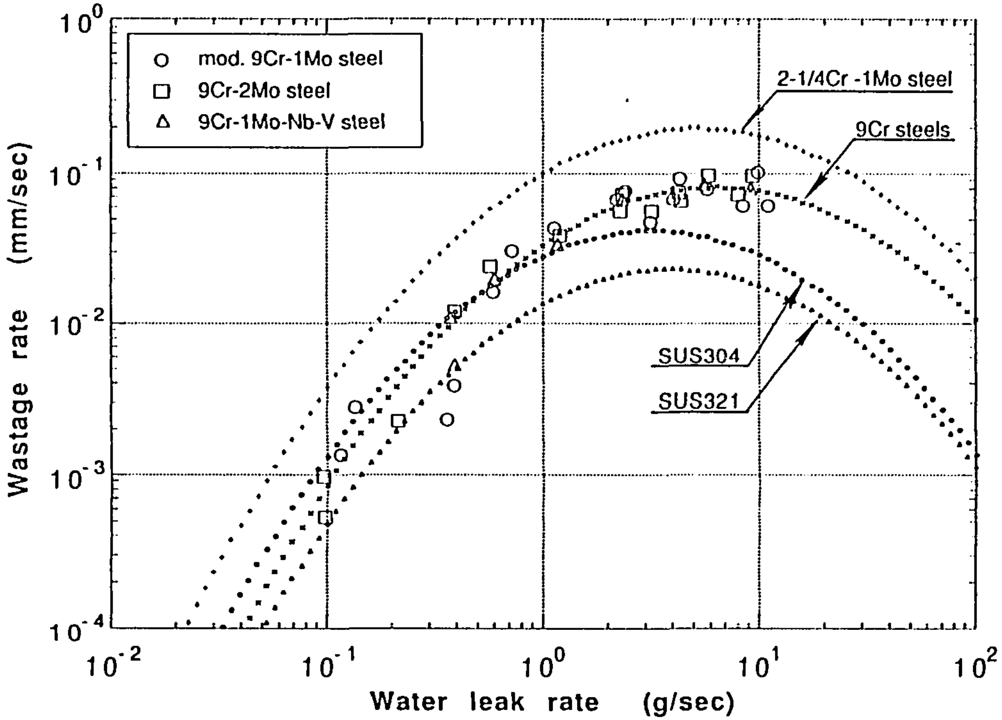


Figure 2 Wastage rate dependence on tube material

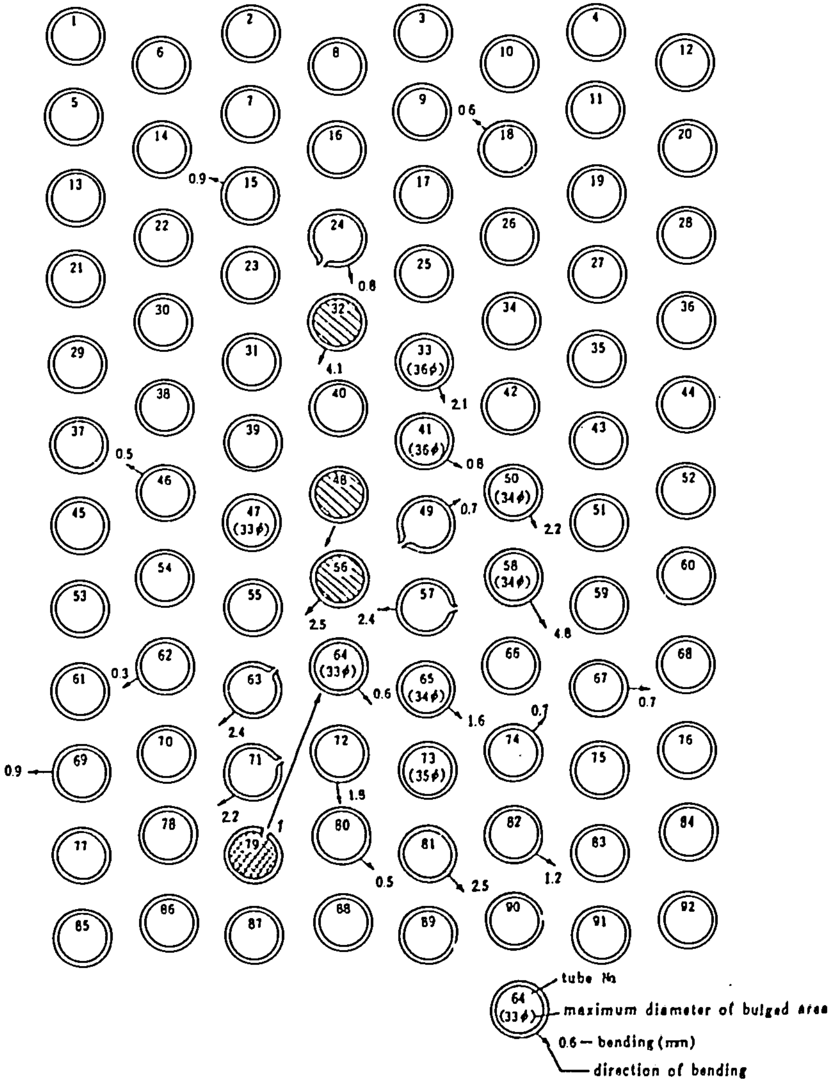


Figure 3 Tube configuration of SWAT-3 Run 19

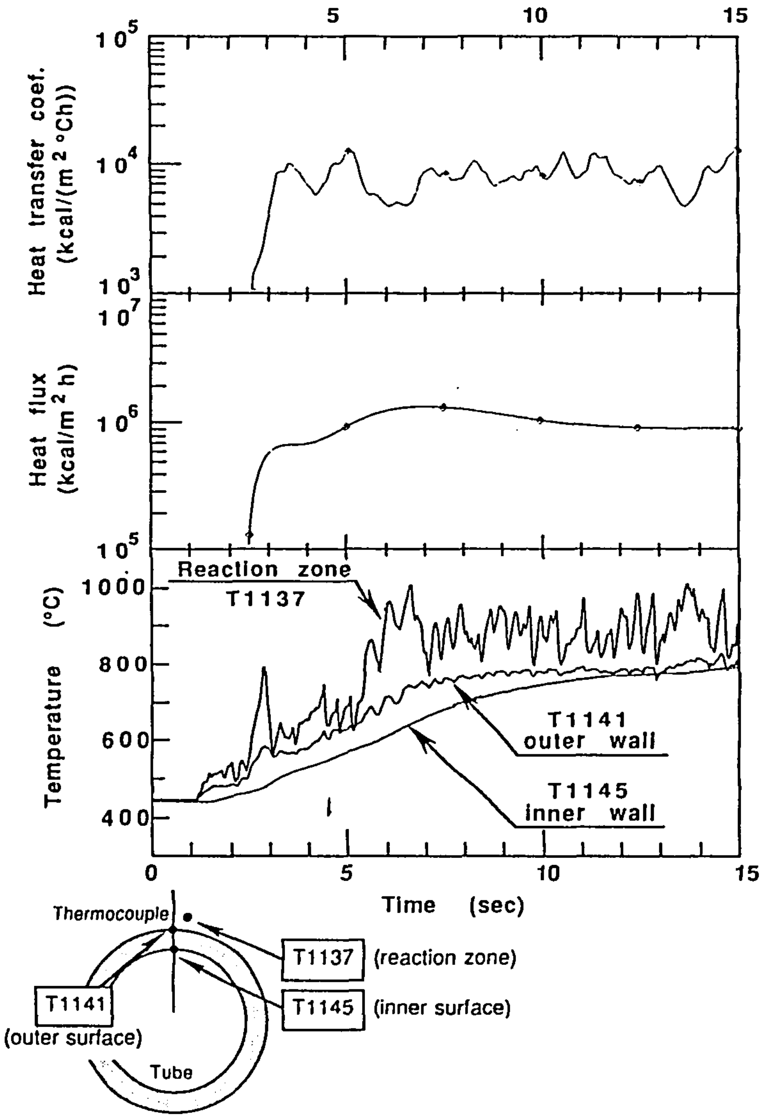
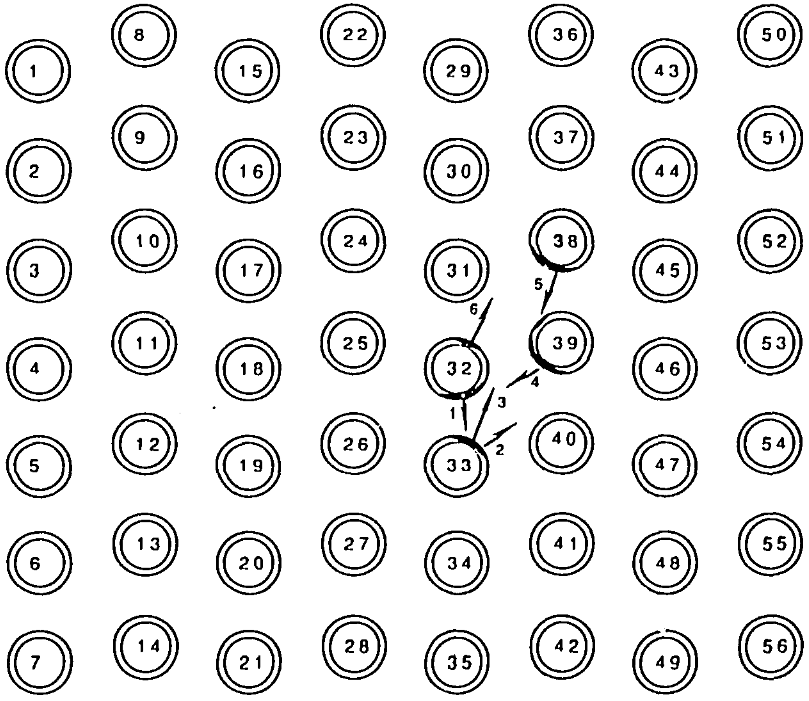


Figure 4 Measurement of heat transfer Coefficient



Ser. No.	Tube No.	time (sec)	leak rate (g/sec)
1	32	0	18
2	33	94	210
3	33	145	470
4	39	168	810
5	38	215	900
6	32	275	-

Figure 5 Proceeding of failure propagation in SWAT-3 Run 14

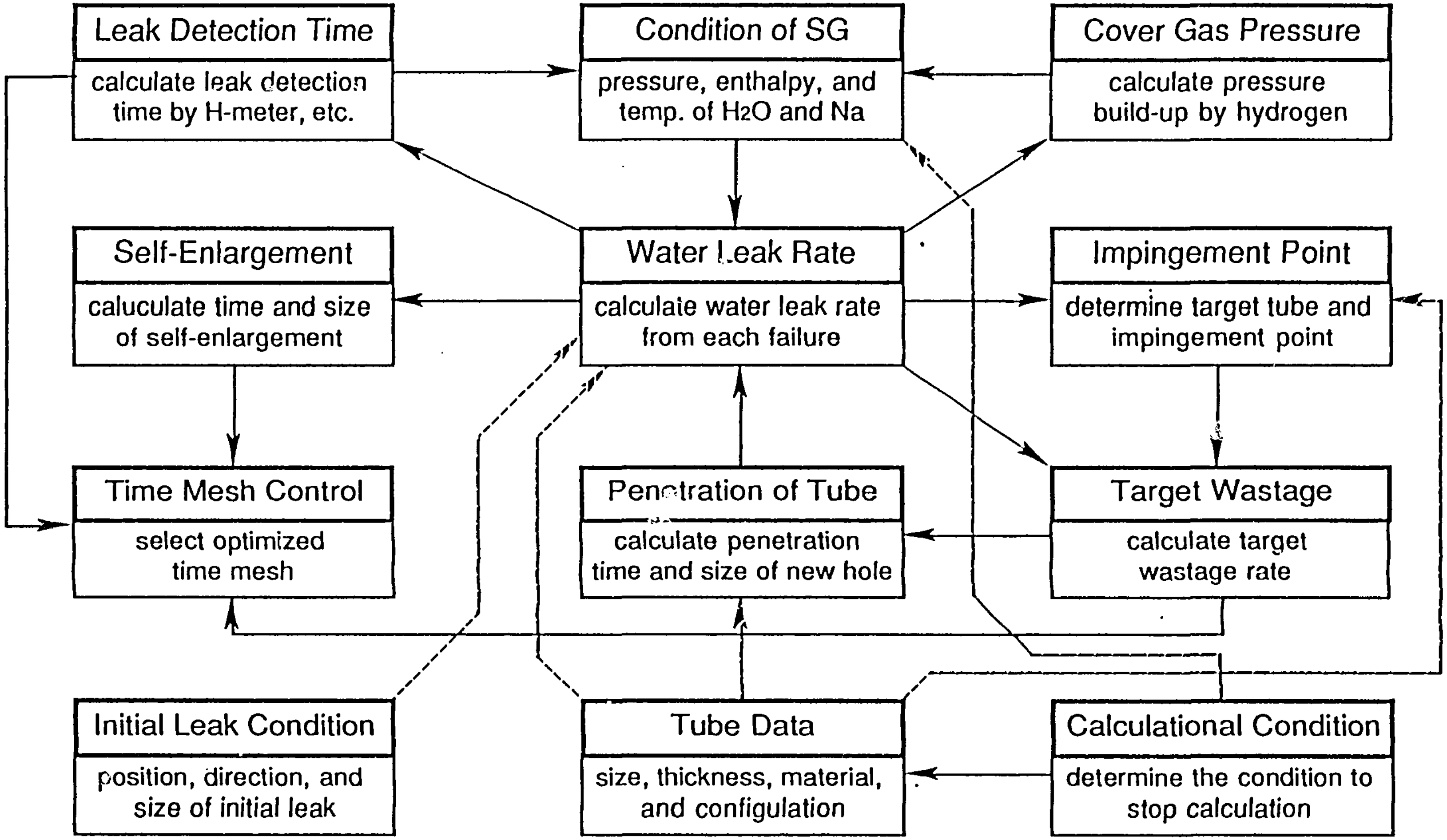


Figure 6 Linkage of LEAP's elments

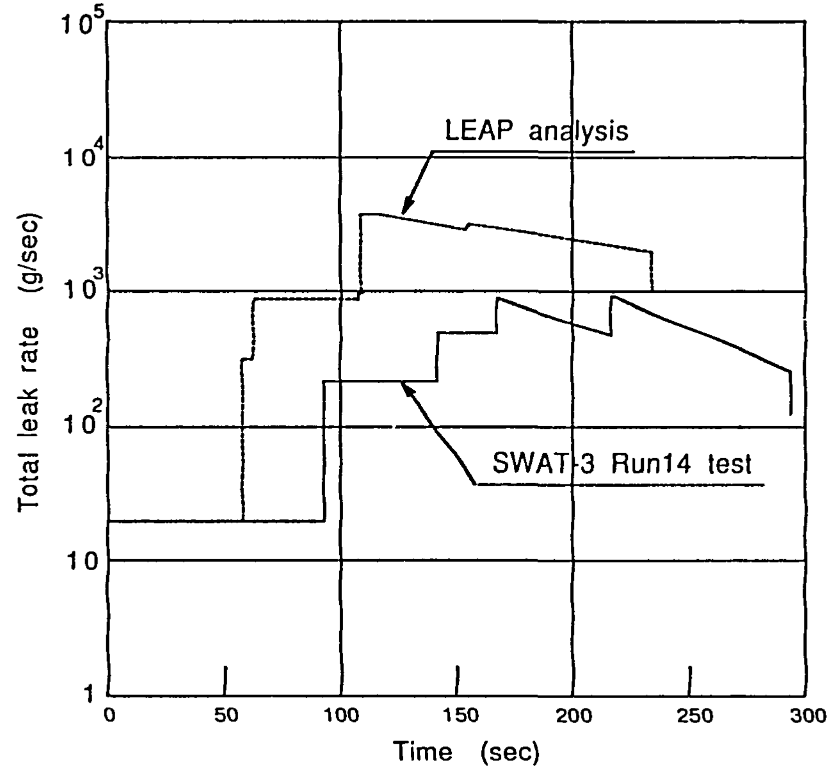


Figure 7 LEAP analysis of SWAT-3 Run 14 test

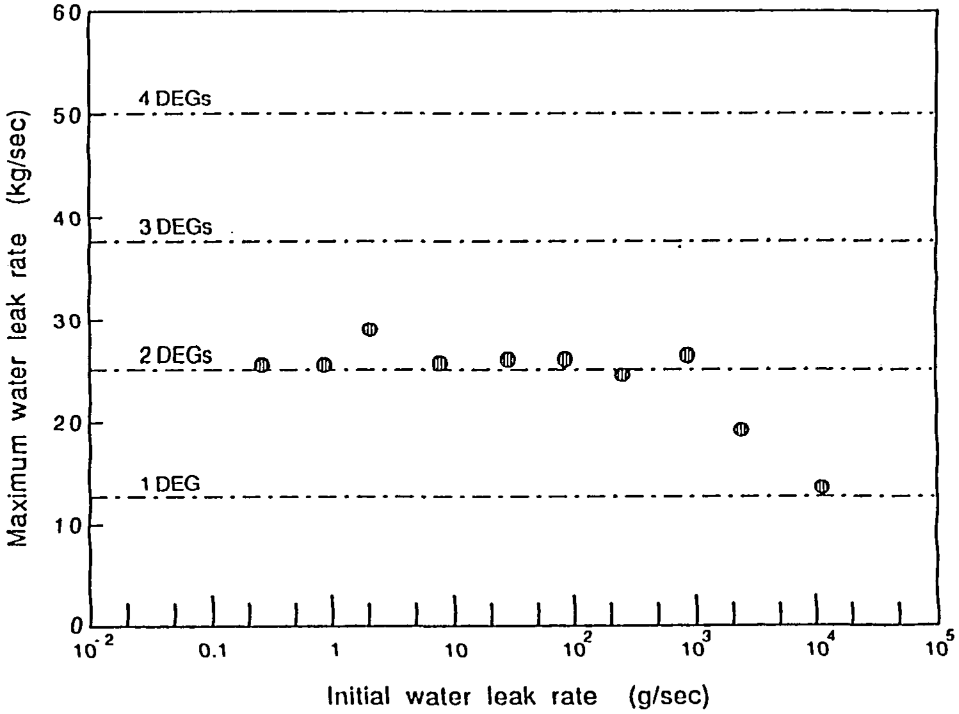


Figure 8 Relation between initial water leak rate and maximum water leak rate by LEAP calculation