I-3214

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ANALYSIS OF LARGE-LEAK TEST SWAT-3 RUN 6 DATA BY
USE OF SODIUM-WATER-REACTION ANALYSIS CODE SWAAM-1

by

Y. W. Shin and H. C. Lin

APPLIED TECHNOLOGY

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Prepared for the
U. S. DEPARTMENT OF ENERGY
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Printed in the United States of America

Available from

U. S. Department of Energy
Technical Information Center

P. O. Box 62

Oak Ridge, Tennessee 37830

Price: Printed Copy \$6.50

ANL-CT--82-4

DE82 014779

Distribution Category:
LMFBR—Structural Materials and
Design Engineering: Applied
Technology (UC-79Th)

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

ANALYSIS OF LARGE-LEAK TEST SWAT-3 RUN-6 DATA BY
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by

Y. W. Shin and H. C. Lin

Components Technology Division

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February 1982

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ANALYSIS OF LARGE-LEAK TEST SWAT-3 RUN-6 DATA BY
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ABSTRACT

The Sodium Water Advanced Analysis Method computer code (SWAAM-I) is used to analyze the large-leak test data SWAT-3 Run-6. The SWAT-3 is the mockup of the secondary system of the Japanese breeder-reactor demonstration plant Monju. The steam-generator design for the Monju reactor was a helical-coil-tube type with a cover-gas space, and the SWAT-3 Run-6 Test vessel simulates this design of the steam generator. The objectives of this work are (1) to examine the adequacy of the SWAAM-I code for the helical-coil-tube steam-generator system, (2) to understand and confirm the understanding of phenomena that have major design implications, and (3) to define needs for additional development of SWAAM-I code capabilities.

The result of this work indicate that, in general, the SWAAM-I code capabilities developed to date are suitable for application to the helical-coil-tube type steam-generator design, but still additional capabilities are needed in order to gain a better understanding of the SWAT-3 injection system. The water-injection system of the SWAT-3 facility is not prototypic to the plant conditions. SWAAM-I capabilities are developed to model plant conditions, and additional capabilities are required to model the atypical design of the SWAT-3 injection system adequately. Response of the sodium-side system of SWAT-3 was well predicted by the code, however, including definition of the source pressures. This indicates the general validity of the SWAAM-I model for the SWAT-3 sodium-system geometry and the soundness of the analytical models that form the bases of the many modules of SWAAM-I.

I. INTRODUCTION

SWAAM-I Code [1] is developed to aid designers in the design of steam-generator systems with respect to the potential occurrence of large-scale sodium-water reactions (SWR's). The design-oriented SWAAM-I code is also a best-estimate code, which can be used for verification or evaluation of a particular design of the secondary system in future licensing procedures. The various code capabilities have been tested during the developmental stage, and, later more extensively, validated by the Large Leak Test Rig (LLTR) Series-II test data [2,3,4]. The LLTR is a mockup of the Clinch River Breeder Reactor (CRBR) secondary system. The CRBR design incorporates straight-tube-type steam generators that do not have free fluid surfaces, which play the major role of limiting the early SWR pressures. The CRBR employs rupture discs instead to limit early source pressures. The pre- and posttest analyses of the LLTR performed tests by the SWAAM-I code showed that the source pressures and the pressures propagated out in the LLTR piping system were accurately calculated in all major respects.

The objectives of this work are to determine if the SWAAM-I capabilities are adequate for the helical-coil-tube-type steam-generator systems and, if not, to define the needs for additional development of the code capabilities. The SWAT-3 system uses a water-injection system not prototypic to Monju and is very difficult to calculate. The measurements obtained from the water-side system are not sufficient to determine the early time-dependent injection rate. Hence the injection rate for the early time needed to perform the analysis of the sodium-side response must be determined analytically. Another major difference between SWAT-3 and LLTR is that the free fluid surface in the cover-gas space of the SWAT-3 reaction vessel limits the peak pressure at the source location, as contrasted to the LLTR, where opening of the rupture disc provides the pressure attenuation. The small length-to-diameter ratio of the SWAT-3 reaction vessel, as compared to the LLTR vessel, together with the tube-support structures that limit flow communications between the divided sections of the reaction vessel, will provide increased multidimensional effects and quite different loading conditions on the structures than the LLTR case. It was of interest, therefore, to see whether SWAAM-I can, with reasonable accuracy, model such geometry of the SWAT-3 vessel and predict pressures at the source as well as in the piping outside the vessel.

II. SWAT-3 FACILITY AND RUN-6 TEST CONDITIONS

The SWAT-3 Test Facility is the mockup of the Japanese Monju secondary system and is located at the PNC Oarai Engineering Center in Oarai. The facility is an ambitious simulation in which the reaction vessel and the piping system are closer to the reactor system in both size and layout than any other similar facilities existent elsewhere in the world today. Many important components are represented in the facility, and the piping system is nearly prototypic to Monju in both the pipe size and the piping layout. A schematic flow diagram of SWAT-3 is shown in Fig. 1. The intermediate heat transport system (IHTS) consists of the major components--the evaporator (EV), the superheater (SH), and the intermediate heat exchanger (IHx)--and the connecting piping. The relief system, consisting of the rupture discs, the reaction-products tank (RT), and the associated piping, is also an important part of the facility. The evaporator is the reaction vessel in which the leak tube is located. The leak tube is connected to the water-injection system, which includes the water heater tank (WH). The rest of the facility includes auxiliary systems such as the sodium-purification system, the nitrogen system used for sodium filling or draining, the sodium-storage system, etc.

The main objectives of the SWAT-3 Test Facility are similar to those of the U. S. Program of LLTR: (1) demonstrate the adequacy of the Monju steam-generator system, (2) develop a data base for a realistic definition of the design-basis leaks (DBL's), and (3) develop a data base for validation of SWR-analysis computer codes. A number of large-leak tests have been performed at the SWAT-3 facility for varying leak and sodium-side conditions. Among the many large-leak test data, Run-3 and Run-5 data were analyzed earlier by the Babcock & Wilcox Company [5], where the main design and fabrication work are being performed for the helical-coil-tube type steam generator. This present work is the continuation of the SWAAM-I code validation performed at ANL using the Run-6 data. The test conditions used

Fig. 1. SWAT-3 Facility Schematic Flow Diagram

for the Run-6 Test are summarized in Table 1. Details of the SWAT-3 Facility and Run-6 Test data can be found in Reference [6].

Table 1. Summary of Run-6 Test Conditions

Item	Description
Internal Structure	Hitachi-manufactured Helical Coil Tube
Leak Location	5th Layer from Bottom (Fluid Level 3070mm)
Water-Injection Conditions	
Rupture-Disc Set Pressures (RD-501, RD-502)	100 kg/cm ² (1420 psi)
Quasi-steady Injection Rate	9.4 kg/s (20.68 lb/s) at 1 sec 8.3 kg/s (18.26 lb/s) at 9.5 sec
Total Water Injected	90 kg (198 lb)
Water-Tank Initial Charge	465 kg (1023 lb)
Duration of Injection	9.5 sec
Water-Heater Temperature	305°C (581°F)
Water-Heater Pressure	154 kg/cm ² (2190 psi)
Sodium System Conditions	
Sodium Temperature	445°C (833°F)
Sodium Flow Condition	Stagnant
Cover-Gas Pressure	
Evaporator	0.5 kg/cm ² gauge (7.11 psig)
Superheater	0.5 kg/cm ² gauge (7.11 psig)
Gas Used for Cover Gas	Argon

A. Water-Injection System

The water-injection system of the SWAT-3 facility is designed to simulate the double-ended-guillotine (DEG) break of steam-generator tubes. (DEG break allows the maximum water-leak rate during the early period.) The injection system uses a thin membrane sleeve placed over the tube location where holes are drilled around the circumference of the tube. Figure 2 shows the three rows of holes on the tube wall (18 holes in all). Figure 3 shows the tubing in the reaction vessel and the pipes connecting to the water-heater tank. The tubings at the helical-coil section and the downcomer section of the reaction vessel join at the upper part to form a tee joint and connect to the pipeline leading to the tank. The rupture disc RD-501 is located directly upstream of the tee. Upon opening of valves V-501 and V-502 at the start of any test, the pipeline upstream of RD-501 first pressurizes due to the water-heater-tank pressure. The tubings downstream of RD-501 are in a near-vacuum condition initially before the

Fig. 2. Rupture-Sleeve Design of Injection System

Fig. 3. Water-Injection System

test. The initiation of the water leak at the leak site (rupture sleeve RD-502) results from opening RD-501 and pressurizing the tubing near RD-502.

The set pressures of the rupture disc and the sleeve are both 100 kg/cm (1420 psi); the tank pressure is 154 kg/cm² (2190 psi). The flow conditions in the tubing inside the reaction vessel, as well as in the other pipes of the water-injection system, will therefore be under dynamic conditions at the time of leak initiation. The initial conditions in the water-system piping are the information necessary to analyze the test data by the SWAAM-I code, and a substantial amount of effort has been expended on this subject during this work.

B. Sodium-Side System

The sodium-side system of the SWAT-3 Facility is a faithful simulation of the Monju secondary system. As shown in Fig. 4, the evaporator is the reaction vessel, which is a 0.4-scale model of the Monju steam generator. As indicated in the figure, the superheater and the IHX are in a much smaller scale than the evaporator. The elaborate piping layout enables the obtaining of data on the attenuation of the pulses and on the interactions in the piping network.

The reaction vessel contains a tube bundle, the same as that of the Monju steam generators, but reduced in size by the 0.4 scale. However, the size and pitches of the individual heat-transfer tubes are maintained the same as the Monju plant. Therefore, the immediate effect of the SWR's on the surrounding structures would be the same in the reduced-scale model of the reaction vessel as in the full-scale unit. The local prototypicality of the tube size satisfies the conditions needed for the DBL consideration. However, the overall response data of the SWAT-3 sodium side will not be directly applicable to the Monju plant steam-generator system design. The sodium side of SWAT-3 uses pipe sizes nearly prototypical, but the layout and the sizes of the various components are not prototypical. The analysis-methods computer codes therefore must be used to translate the data from the reduced-scale tests to the design of the actual plant units. Figure 5 shows details of the internal structures used for the Run-6 Test and the pressure-transducer locations in the evaporator.

C. Pressure-Relief System

The pressure-relief system is part of the general sodium-side system and relieves the system pressures and the reaction products. The rupture discs connected to the reaction vessel and superheater at the cover-gas space (RD-601 and RD-602, respectively) will open and activate the relief system when the cover-gas space pressure reaches the set pressures of the rupture discs. The relief-system piping is initially empty and connects to the reaction-products tank RT (refer to Fig. 1). The cyclone separator is part of the RT, and rupture disc RD-603 relieves the hydrogen gas in the RT to the atmosphere, where the hydrogen gas ignites and burns. Since the pressurization of the cover-gas space in the reaction vessel takes about 0.5 sec or more and the pressure waves generated by an SWR diminish substantially during that time, the present analysis of the SWAT-3 data does not include the slow transients taking place after the rupture disc opens.

Tag.	Location	Direction	Night
P 1111	Pres. Tap	90°	FL2200
F 1112			FL2550
F 1113			FL 3000
F 1114			FL4400
F 1115		90°	FL5800
P 1131		245°	FL2200
P 1132		270°	FL2550
P 1133			FL 3000
P 1134			FL4400
F 1135	Pres. Tap	270°	FL5800
PK1101	Coll	90°	FL 2830
PK1102	Coll	90°	FL4470
PK1103	C.P	-	FL2570
PK1104	C.P	-	FL5800

Fig. 5

Internal Structures and Pressure-
Transducer Locations in Evaporator

The relief-system response data of the Run-6 test therefore are not analyzed in this work.

III. ANALYSIS OF WATER-INJECTION RATES

As described in Sec. I, the transient flow of blowdown taking place in the water-injection system of SWAT-3 can be divided into two parts: (1) the initial filling transient and (2) the actual blowdown. The filling transient lasts until the rupture sleeve (RD-502) opens, at which time the blowdown transient starts. The flow distribution at the end of the filling transient establishes the initial conditions for the blowdown phase of the water-injection-system transient. A rigorous treatment of the water-injection-system analysis therefore includes calculations of both the filling transient and the subsequent blowdown.

We had undertaken an ambitious approach and started development of the SWAAM-I capabilities to handle the aprototypical features of the SWAT-3 water-injection system. The main developments made were: (1) tee-joint pipe connection, (2) inclusion of noncondensable gas, (3) in-line rupture-disc modeling, and (4) steam-table routines for extremely low pressures. Calculations of the filling transient then were attempted with the new capabilities of SWAAM-I. The effort, however, was not very successful, because numerical difficulties were encountered in the hybrid scheme of the SWAAM-I water-side module. The high-strength shock waves propagating into the low-pressure region of the pipeline upstream of the rupture disc (RD-501) could not be calculated accurately when the shock waves reflected from the rupture disc. The calculation could not proceed very long beyond the shock reflection, because the scheme eventually went unstable. The numerical scheme has a certain amount of numerical viscosity in the finite-difference part of the SWAAM-I module that enables the calculation of shock waves. A close examination of the difficulties revealed that the shock strength involved in the filling transient was excessively high and no quick fixes were successful to carry on a stable calculation. It was then decided that the problem requires a careful study of the hybrid numerical scheme, which is considered outside the scope of the present work.

Next, the calculation of the filling transient was skipped, and the blowdown transient was calculated with approximate initial conditions estimated from the test results and numerical experiments. The potential uncertainties resulting from the approximate initial conditions and other important parameters were examined by parameter studies. Based on the calculations, a leak rate was established that is finally used for calculation of the source pressures and the pressure transients of the sodium side. In the following, the details of the blowdown calculations and the parameter studies are given.

A. SWAAM-I Model for the SWAT-3 Water-Injection System

1. Model Description

The SWAAM-I model for the SWAT-3 water-injection system is shown in Fig. 6. The model includes all dimensional details and the pipe-junction conditions present in the system. The possible flow restrictions at valve

locations V-501 and V-502 are modeled as orifice junctions. Junction 9 at RD-501 is modeled as an in-line rupture-disc junction, where the junction acts as a closed-end junction until the disc opens. The disc opens when the junction reaches the disc set pressure, and the junction subsequently becomes either an orifice junction (if the disc is partially opened) or a dummy junction (if the disc is opened fully). A same-size piping is used from the water-heater tank to junction 11, except pipe 4. The pipe reduces at junction 11. Junction 12 is the branching point where the heat-transfer tubing of the reaction vessel starts. Flow diverts at the branching point to the downcomer and the helical-coil-section tubing. The rupture sleeve RD-502 (junction 17) is the leak location, which is modeled as a double-ended break. Pressure-transducer locations in the helical-coil section are modeled as junction points. A total of 20 pipes and 20 junctions are used to model the water-injection system. Table 2 shows the dimensions of the individual pipes and the types of junctions.

2. Tee-Junction, Tee-Break Boundary Formulation

The branching point is modeled as a tee junction. The tee-junction capability of SWAAM-I was newly developed for use in modeling the SWAT-3 data analysis. At first, the tee-junction methodology was coded for subsonic flow cases only. But later it was found that flow choking takes place in one of the branches, and recoding was necessary to continue the calculation. The methodology to treat the tee junction with flow choking is briefly discussed in Appendix A. The rupture-sleeve arrangement used in the SWAT-3 water-injection system can best be calculated by modeling it as a special tee junction, called here the tee-break boundary. The rupture-sleeve arrangement is viewed as a tee with the third pipe having no physical length. The third pipe of the regular tee junction is replaced by a break-boundary condition. Figure A-4 describes the flow configuration. The solution methodology for the tee-break boundary was developed and is briefly described in Appendix A. Figure A-5 shows the schematic of the solution methodology for the tee-break boundary. The methodology rigorously accounts for the wave interactions of the two pipe branches with the break-boundary conditions.

3. Actual Calculation Models

In actual calculations, simplified models were used as shown in Fig. 7. The two-pipe model shown in Fig. 7a is the simplest model considered. The short length of pipe, pipe 11 of Fig. 6, is treated as the same size pipe as the upstream pipe in all cases shown in Fig. 7. Pipe 2 of the two-pipe model uses an equivalent length based on certain simplifying assumptions. A simple calculation is made, and the general expression is

$$L = \frac{(1 + \frac{A_2}{A_1})^2}{\frac{L_1}{L_2} (\frac{A_2}{A_1})^{5/2} + 2(\frac{L_1}{L_2})^{1/2} (\frac{A_2}{A_1})^{5/4}} (\frac{A}{A_1})^{1/2} L_1, \quad (1)$$

Fig. 6

SWAAM-I Model of SWAT-3 Run-6
Test Water-Side System

(a) TWO-PIPE MODEL

(b) THREE-PIPE MODEL

(c) THREE-PIPE / TEE-BREAK BOUNDARY MODEL

Fig. 7. Simplified SWAAM-I Calculational Models

Table 2. SWAAM-I Model Water-Side System Dimensions for SWAT-3

Pipe No.	Jct. No. (Jct. Type)	Jct. No. (Jct. Type)	Length (ft)	ID (ft)	Relative Roughness
1	1(3)*	2(5)	1.8515	0.2924	0.0001
2	2(5)	3(5)	8.1533	0.2924	0.0001
3	3(5)	4(7)	6.9393	0.2924	0.0001
4	4(7)	5(7)	4.5934	3.2920	0.0001
5	5(7)	6(5)	2.4115	0.2924	0.0001
6	6(5)	7(5)	2.6248	0.2924	0.0001
7	7(5)	8(5)	1.5257	0.2924	0.0001
8	8(5)	9(5)	1.0903	0.2924	0.0001
9	9(5)	10(5)	1.0752	0.2924	0.0001
10	10(5)	11(7)	1.5978	0.2924	0.0001
11	11(7)	12(12)	3.0185	0.1985	0.0001
12	12(12)	13(5)	5.8762	0.0964	0.0001
13	13(5)	14(5)	35.1363	0.0964	0.0001
14	14(5)	15(5)	26.2349	0.0964	0.0001
15	15(5)	16(5)	3.3302	0.0964	0.0001
16	16(5)	17(5)	0.5167	0.0964	0.0001
17	17(1)	18(5)	0.5200	0.0964	0.0001
18	18(5)	19(5)	3.3300	0.0964	0.0001
19	19(5)	20(5)	1.4000	0.0964	0.0001
20	20(5)	12(12)	18.9600	0.0964	0.0001

*Jct. Types: 1 - Break End, 3 - Reservoir, 5 - Orifice in Pipe,
7 - Area Change, 12 - Tee Jct.

where subscripts 1 and 2 refer to the two branches of pipe to be lumped, and quantities with no subscripts refer to the equivalent lumped pipe. A is the cross-sectional area of the pipe, and L is the length. In the SWAT-3 injection system, $A_1 = A_2$, and it is desirable to have $A = A_1 + A_2$. Then $L = 54.47$ ft, since $L_1 = 24.11$ ft and $L_2 = 71.00$ ft. The three-pipe model shown in Fig. 7b is the same as the elaborate model of Fig. 6, except that the size of Pipe 11 is approximated by the upstream pipe size. The leak flow is the double-ended break. Because of the possible interaction of flow in the two branches of the pipe at the leak site during a blowdown, the three-pipe model given in Fig. 7b is not a rigorous model. The three-pipe/tee-break model shown in Fig. 7c improves this shortcoming by allowing the flow interaction. A short-length pipe is added to form a tee junction. The other end is the break end. The cross-sectional area of the added pipe is the sum of the two upstream pipes (approximately equals the total hole areas of the rupture sleeve). The reason for considering the three-pipe/tee-break model is that, although the tee-break boundary formulation was developed as described in Appendix A, the coding has not yet been completed. The three-pipe/tee-break model closely simulates the tee-break boundary condition as long as the third pipe section is kept relatively short.

4. Initial Conditions

The initial conditions for the blowdown calculation of the SWAT-3 water-injection system were determined by a combination of the test data and numerical experiments. Parametric studies were also conducted later to gain confidence on the choice of the initial conditions. The test data for the water-injection-system response are discussed in Appendix B. Briefly, the data indicate the following:

- a. The flow conditions in the piping system at the time of leak initiation are not uniform and are highly dynamic.
- b. The enthalpy levels of fluid in the pipes can be much greater than those of the subcooled water at the water-heater tank.
- c. There could be a significant heat transfer from the sodium to the water/steam.
- d. A quasi-steady condition may be reached within 100-300 msec.

From the pressure profiles of Fig. B-8, a uniform pressure of 1420 psia (100 kg/cm²) was assumed for simplicity. A number of SWAAM-I runs were made for various enthalpy levels, using the three calculational models discussed above. The result of the calculations led to the choice of an initial quality of 20%. This choice, together with the assumed pressure of 1420 psia, appears to approach the quasi-steady leak rate 20.7 lb/sec (9.4 kg/sec) indicated by the SWAT-3 Test Report [6].

B. Results of SWAAM-I Calculations and Discussion

The results of the Three-Pipe Model are shown in Figs. 8-10. Figure 11 shows the results of the Three-Pipe/Tee-Break Boundary Model and compares them to the results of the Three-Pipe Model. Results of the Two-Pipe Model and the Three-Pipe Model are compared in Fig. 12. As shown in Fig. 8, the Three-Pipe Model result indicates that the initial leak is about 19 lb/sec but gradually increases to about 40 lb/sec at about 160 msec when the calculation was terminated. The increase in the leak rate was considered entirely due to the deficiency of the Three-Pipe Model. The Three-Pipe Model assumes a double-ended break and allows no flow interaction in the two branches of pipe. The interface locations of the subcooled water and the two-phase mixture are shown in Fig. 9. It is seen that the interface moves toward the break end and stays near the break end for the short downcomer tube section. This results in an increase of the leak rate in the downcomer tube section, as indicated in Fig. 8. The pressure profiles shown in Fig. 10 indicate that the conditions near the break settle to a quasi-steady condition near the end of the computation. Approach to the quasi-steady condition is much faster for the long branch than for the short branch.

To properly account for the flow-limiting conditions of the SWAT-3 rupture-sleeve arrangement, the tee-break boundary model was developed and calculated for the same initial conditions. The results for the 100% area opening, namely the total rupture-sleeve opening being the sum of cross-sectional areas of the two tube branches, indicated that the initial leak calculated was about 24.5 kg/sec (see Fig. 11). The break flow through the rupture-sleeve holes is a highly three-dimensional problem, and a one-dimensional modeling requires an empirical correction as to the effective hole area. An 80% effective hole area was calculated, and the result is shown in Fig. 11. The initial leak is reduced to 21.5 kg/sec. It is

Fig. 8. SWAAM-I Result for Initial Leak Rates
(1420 psia and 20% Initial Quality)

Fig. 9. Subcooled Water/Two-phase Interface Locations

Fig. 10. Pressure Profiles during Blowdown Transient

Fig. 11. Effects of Model Simplifications

clearly seen that the flow-limiting ability of the tee-break boundary model yields a much slower increase in the leak rate than the double-ended break-flow model. The two-pipe model has a similar flow-limiting ability, and its result is shown in Fig. 12. The two-pipe model result shows a fast convergence to a quasi-steady condition without the persistent rise in the leak rates shown in both the three-pipe and the three-pipe/tee-break models. The criteria were to find the initial quality that yields the quasi-steady leak rate approaching 20.7 lb/sec given by the Run-6 Report [6]. Judging from the results obtained from the three different calculational models of the SWAAM-I water-side module, it appears that the 1420-psia and 20%-quality steam/water mixture is nearly the right condition to use as the initial condition. The nonuniform dynamic conditions existing in the pipes at the time of leak initiation cannot be derived from the test results. They must be calculated, and they will be the subject of future work recommended in this report.

C. Parametric Studies

This section studies the effects of the initial enthalpy and the effects of wall heat transfer. Figure 13 shows the results for the saturated water condition at 1420 psia as the initial condition. The results of both the three-pipe and the two-pipe models are shown. The leak rates are much higher than the 20% quality case, although the general trend is similar. Figure 14 shows the effects of the initial subcooled-water condition. Again, the leak rates are much higher than the 20% quality case. Figure 15 compares leak rates for the individual pipes as calculated by the three-pipe model. The comparison shows that the 20% quality of the initial condition is the closest to the quasi-steady leak rate of 20.7 lb/sec.

The effects of wall heat transfer are shown in Fig. 16, where the results from the two-pipe model for the two levels of wall-heat transfer are compared with similar result for no wall-heat transfer. Wall-heat transfer tends to increase the longer-term leak rates, although the magnitudes of the increases are not significant. The higher level of heat-transfer rate (15×10^6) considered is about the maximum wall-heat transfer for the given sodium-to-water temperature differential of 252°F.

IV. ANALYSIS OF SODIUM-SIDE RESPONSES

The leak rates from the water-injection system of the SWAT-3 Facility were discussed in Sec. III. From the results of the SWAAM-I calculations, the parametric studies performed, and the test data, it was concluded that the early time-dependent leak rate could not be determined very accurately. But the analyses indicated that the early leak rate quickly approaches the quasi-steady leak rate of 20.7 lb/sec [6], as early as 100-300 msec. Leak rates for earlier than these times depend strongly on the initial conditions in the injection-system tubes, especially in the heat-transfer tubes near the leak, and the initial conditions are not very accurately determinable within the scope of this report. Therefore, the leak rate used for calculation of the sodium-side transient is constructed from the results of analyses and the test data. A simple leak rate, constant at the quasi-steady leak rate of 20.7 lb/sec, was used for the calculation

Fig. 12. Effects of Model Differences
(20% Quality Initial Condition)

Fig. 13. Effects of Model Differences (Saturated
Water Initial Condition)

Fig. 14

Effects of Model Differences
(Subcooled Water Initial
Condition)

Fig. 15. Effects of Initial Conditions
on Leak Rates

Fig. 16. Effects of Wall Heat
Transfer on Leak Rate

of the source pressure and the propagation of the source pressure throughout the SWAT-3 piping network. The possible uncertainties in the early leak rates and their impacts on the response of the sodium-side system are studied next by varying the early leak rates.

A. SWAAM-I Model for SWAT-3 Sodium-Side System

Figure 17 shows the SWAAM-I model for the SWAT-3 sodium-side system. The model includes the active sodium-filled pipes as well as the relief-line pipes, where no sodium is filled initially. Sodium fills the relief line only when the rupture discs fail and open during the transients. The dimensions of the pipes for the SWAAM-I model are listed in Table 3. The reaction vessel is modeled by two separate channels of flow to account for the limited flow communication between the adjacent sections due to relatively solid tube-support structures. The quadrant that contains the leak site is separated from the remaining three quadrants in the model. The three quadrants are then lumped together to form the parallel flow path to the faulted quadrant containing the leak. The two channels of flow join both up and down at the plena. The upper plenum joins next to the cover-gas junction modeled as a variable-pressure surge tank. The IHX and superheater units are relatively small in diameter and are simply modeled as single-channel pipes. The relief system is connected to both the reaction vessel and the superheater at the cover-gas region. Since the rate at which the cover-gas region pressurizes is slow, the rupture discs do not open until long after initial pressure transients are over. (Rupture discs open at about 1/2 sec into the transient.) SWAAM-I analyses are limited to the initial 200 msec or less and hence do not include the relief-system response.

The initial conditions used for the computation are the stagnant pure liquid sodium. The constant leak rate of 20.7 lb/sec was input, and the source pressures and the pressures at various points of the system were calculated. Note that the sodium-side system has a complete flow loop.

B. Results of SWAAM-I Calculations and Discussion

Modeling of the sodium-water reaction and propagation of the resulting pressure pulses in the SWAT-3 system require input of a single parameter other than the physical dimensions of the piping system. The single parameter to be input is the reaction-rate coefficient Λ defined by the model equation

$$\frac{dm'}{dt} = \frac{\Lambda A_f \bar{m}}{V}. \quad (2)$$

Here, m' is the water mass undergoing the reaction, $\bar{m}$ the water mass remaining in the reaction bubble and available for reaction, A_f the surface area of the reaction bubble, and V the volume. A spherical shape is assumed for the reaction bubble. Other parameters to be input to describe the reaction in detail are the hydrogen conversion ratio (B) and the stoichiometric coefficient (C_3) defined by the general reaction equation as follows:

Table 3. SWAAM-I Model Sodium-Side System Dimensions

Pipe No.	Jct. No. (Jct. Type)*	Jct. No. (Jct. Type)*	Length (ft)	ID (in.)	Thickness (in.)	Net Flow Area (in. ²)
1	1(17)	2(6)	1.53	22.52	0.500	0
2	2(6)	3(6)	1.48	22.52	0.500	0
3	3(6)	4(6)	1.15	22.52	0.500	0
4	4(6)	5(3)	1.67	22.52	0.500	0
5	5(3)	6(1)	0.67	7.87	0.500	0
6	1(17)	7(6)	3.06	22.52	0.500	0
7	7(6)	8(6)	4.59	22.52	0.500	0
8	8(6)	9(3)	0.50	22.52	0.500	0
9	9(3)	10(6)	0.50	40.73	0.500	0
10	10(6)	11(6)	9.20	40.73	0.500	0
11	11(6)	12(6)	1.50	40.73	0.500	0
12	12(6)	13(6)	1.15	40.73	0.500	0
13	13(6)	5(3)	1.67	40.73	0.500	0
14	9(3)	14(5)	6.70	51.18	0.500	0
15	6(1)	15(6)	2.20	8.00	0.260	0
16	15(6)	16(3)	1.64	8.00	0.260	0
17	16(3)	17(1)	13.78	8.00	0.260	0
18	17(1)	18(6)	6.50	2.00	0.154	0
19	18(6)	19(3)	4.00	2.00	0.154	0
20	19(3)	20(6)	6.27	2.00	0.154	0
21	20(6)	21(6)	7.05	2.00	0.154	0
22	21(6)	22(6)	3.45	2.00	0.154	0
23	22(6)	26(1)	0.59	2.00	0.154	0
24	16(3)	23(6)	0.82	2.00	0.154	0
25	23(6)	24(7)	17.72	2.00	0.154	0
26	19(3)	25(7)	1.00	2.00	0.154	0
27	26(1)	27(6)	7.42	7.87	0.323	0
28	27(6)	28(1)	7.42	7.87	0.323	0
29	28(1)	29(6)	0.62	2.00	0.154	0
30	29(6)	30(3)	41.33	2.00	0.154	0
31	30(3)	31(6)	2.62	2.00	0.154	0
32	31(6)	32(1)	7.53	2.00	0.154	0
33	32(1)	34(3)	6.08	8.00	0.260	0
34	30(3)	33(7)	2.51	2.00	0.154	0
35	34(3)	35(6)	3.09	31.50	0.750	0
36	35(6)	36(6)	3.09	31.50	0.750	0
37	36(6)	37(1)	3.09	31.50	0.750	0
38	34(3)	44(5)	4.43	31.50	0.750	0
39	44(5)	45(7)	2.13	5.91	0.200	0
40	37(1)	38(6)	6.56	8.00	0.260	0

TABLE 3. SWAAM-I Model Sodium-Side System Dimensions (cont'd)

Pipe No.	Jct. No. (Jct. Type)*	Jct. No. (Jct. Type)*	Length (ft)	ID (in.)	Thickness (in.)	Net Flow Area (in. ²)
41	38(6)	39(6)	18.10	8.00	0.260	0
42	39(6)	40(6)	8.56	8.00	0.260	0
43	40(6)	41(6)	13.62	8.00	0.260	0
44	41(6)	42(6)	3.08	8.00	0.260	0
45	42(6)	9(3)	5.41	8.00	0.260	0
46	14(5)	43(10)	3.74	12.00	0.400	0
47	46(13)	47(6)	1.93	12.00	0.400	0
48	47(6)	48(6)	8.79	12.00	0.400	0
49	48(6)	49(6)	8.84	12.00	0.400	0
50	49(6)	50(3)	8.20	12.00	0.400	0
51	51(13)	52(6)	4.58	6.00	0.260	0
52	52(6)	53(1)	32.15	6.00	0.260	0
53	53(1)	54(1)	2.62	6.00	0.260	0
54	54(1)	50(3)	13.29	6.00	0.260	0
55	50(3)	55(6)	4.10	12.00	0.400	0
56	55(6)	56(1)	5.41	12.00	0.400	0
57	56(1)	57(1)	3.94	12.00	0.400	0
58	57(1)	58(6)	7.53	12.00	0.400	0
59	58(6)	59(6)	5.91	12.00	0.400	0
60	59(6)	60(8)	8.69	12.00	0.400	0

*Jct. Types: 1 - Area Change, 3 - Tee Jct. (3 to 6 pipes),
5 - Surge Tank, 6 - Dummy Jct., 7 - Closed End,
8 - Conts. Press., 10 - Rupture Disc, 13 - First Jct.
in Relief System, 17 - Water Injection Source

However, from the existing large-leak data and other qualitative arguments, the following are reasonable values for SWAAM-I inputs:

$$B = 0.65; \quad (4)$$

$$C_3 = 0. \quad (5)$$

Other coefficients in Eq. 3 are then determined internally in SWAAM-I by taking the mass balance of individual species. A good input for the posttest analysis of LLTR Series-II Test A-2 was found to be $\Lambda = 5.0$ ft/sec. The same input was tried, but the result indicated that it might be somewhat too high a value for the SWAT-3 reaction vessel. The diameter of the SWAT-3 reaction vessel is much greater than that of the LLTR Series-II

reaction vessel. A smaller value, $\Lambda = 2.6$ ft/sec, was therefore used for a reference computation of the SWAAM-I model.

The pressure histories for several selected locations of the system, as obtained from the SWAAM-I calculations, are shown in Figs. 18-23, where the test data are also given for comparison. Figure 18 shows the results for a point closest to the leak position (P1113 is 1.53 ft below the leak site). The agreement on the peak pressure is seen to be very good. However, the subsequent pressures are seen to be significantly lower than the calculated pressures. We do not find a clear explanation for this discrepancy. However, the uncertainties in the early leak rate and the multidimensional flow effects at the upper and lower plena are the likely causes for the discrepancy. The small openings in the tube-support structures that permit some flow communications circumferentially can also contribute to the noted discrepancy. Figure 19 shows the calculated result for the same transducer location P1113 for a longer duration 160 msec. The pressure history at P1001, right below the lower plenum in the piping, is shown in Fig. 20, where the test data are also given. The pulse arrival time is in good agreement. Otherwise, both the pulse heights and phases are not in good agreement. Again, we are not able to explain the discrepancy. The three-dimensional geometry in and near the lower plenum, which is modeled one-dimensionally, is considered to be the most important cause for the discrepancy. Figure 21 shows the longer-term pressure history for the same location. The SWAAM-I prediction shows that cavitation effects are present for the entire transient, while the test data show no sign of cavitation. Moreover, the level of pressure is higher in the test data than in the SWAAM-I prediction. The disagreements noted can be due to the adverse presence of noncondensable gas that could have existed in the piping for the Run-6 Test [6]. The SWAAM-I calculation is based on the sodium as the initial condition, while tests included two-phase flows in some part of the piping.

Figures 22 and 23 show the pressure histories at P1301 near the lower plenum of the IHX. The arrival times of the initial pulse as well as the subsequent pulses are grossly in disagreement. To check if the discrepancies are indeed due to the additional compressibility resulting from the noncondensable gas, the test data for Run-5 Test [7] are also shown in Fig. 23. The Run-5 Test involves a much larger heat-transfer tube (and an accordingly greater leak rate) and shows a greater initial peak pressure. The pulse arrival time, however, shows a good agreement with the SWAAM-I prediction for Run-6. Since all other conditions are essentially the same between Run-5 and Run-6 Tests, it is concluded that the late arrival of the initial pulse shown in Run-6 data is due to the reduced sonic speed. The cavitation effects subsequent to the initial pulses predicted by SWAAM-I are also present in the Run-6 data.

C. Parametric Studies

Basically, two areas in which main uncertainties potentially exist can affect the source pressures. The first is in the input value for the reaction-rate coefficient parameter Λ . For the calculation of the reference run discussed above, $\Lambda = 2.6$ ft/sec was used. A suitable value for the LLTR Series-II A-2 Test [4] was found to be $\Lambda = 5.0$ ft/sec. It was of interest to examine if the same value of Λ would be applicable to both SWAT-3 and

SWAAM-I Model for SWAT-3
Run-6 Sodium-Side System

Fig. 18. Pressure History of SWAT-3
Run-6 at P1113 ($\Lambda = 2.6$,
 $B = 0.65$, $W = 20.68$) --
Early Transient

Fig. 19. Pressure History of SWAT-3
Run-6 at P1113 ($\lambda = 2.6$,
 $B = 0.65$, $W = 20.68$) -- Long-
Term Transient

Fig. 20. Pressure History of SWAT-3 Run-6 at P1001 ($\Lambda = 2.6$, $B = 0.65$, $W = 20.68$) -- Early Transient

Fig. 21. Pressure History of SWAT-3 Run-6 at P1001 ($\Lambda = 2.6$, $B = 0.65$, $W = 20.68$) -- Long-Term Transient

Fig. 22. Pressure History of SWAT-3 Run-6 at P1301 ($\Lambda = 2.6$, $B = 0.65$, $W = 20.68$) -- Early Transient

Fig. 23. Pressure History of SWAT-3 Run-6 at P1301 ($\Lambda = 2.6$, $B = 0.65$, $W = 20.68$) -- Long-Term Transient

LLTR Series-II systems (the possibility for a universal value of Λ). Figure 24 shows the results of the two values of Λ , 2.6 and 5.0 ft/sec, for the same constant leak rate of 20.7 lb/sec. A higher value of Λ merely increased the pressures without affecting the time factor. The second main area in which the uncertainty lies is the early leak rate. To study the effects of the early leak rate, the leak rate was varied from the constant 20.7 lb/sec as follows: (1) initially higher leak rate, 30 lb/sec at $t = 0$ linearly decreasing to 20.7 lb/sec over 20 msec; (2) initially lower leak rate 10 lb/sec at $t = 0$ linearly increasing to 20.7 lb/sec over 20 msec. A 20-msec transition to the constant leak rate is chosen since the most significant initial transient takes place during this time. The result of this parameter study is shown in Fig. 25. Again, the effects are raising or lowering the early pressures. The pressures for larger times are progressively less affected by the perturbation of early leak rates.

A combination of the two main areas of uncertainty is studied next. We considered $\Lambda = 5.0$ ft/sec with the leak-rate perturbation to give a lower initial leak rate (perturbation (2) above), and the result is shown in Fig. 26. The result of SWAAM-I calculations obtained for the combination of the two inputs shows that the source pressure agrees very well with the reference case (constant leak rate). It is highly possible that, for the initial 20 msec or less, the early leak rate in the Run-6 injection system could have well been significantly less than the measured quasi-steady leak rate of 20.7 lb/sec, especially due to the low-pressure and high-energy condition that existed in the injection tubing at the time of leak initiation. This leads to a possibility that $\Lambda = 5.0$ may be a universal value applicable for both the LLTR Series-II and SWAT-3 systems. This possibility must be further examined by refining the early leak rate of the SWAT-3 Run-6 Test and applying the SWAAM-I code to other large-leak tests using different sizes of the reaction vessel.

V. DISCUSSION AND CONCLUSION

SWAT-3 large-leak experiments are valuable sources of test data that pertain to the helical-coil-type steam-generator design with cover-gas space. Because of the near-prototypical representation of the pipelines and the IHTS components, the data from SWAT-3 are just as valuable to the development of other designs of steam generators as to the helical-coil design. The primary objective of this work was to validate the SWAAM-I code for its prediction capabilities for the early transients and the system response for the duration of transients when the wave propagation is the dominant mechanism of energy transport. A typical large-leak excursion can be divided into the three main parts of the event. The first part is the water-side transient that determines the magnitude of energy input to the shell-side sodium system, or that determines the time-dependent leak rate. The second part is the chemical reaction and the generation of the reaction products. Depending on the response of the surrounding liquid sodium, the generation of reaction products and the heat of reaction produce high-pressure pulses that subsequently propagate out through the shell-side system. The third part is the response of the liquid sodium in the shell-side system. A strong coupling exists between the growth and dynamics of the reaction bubble and the shell-side sodium. However, no coupling exists in most cases between the water-side system and the reaction bubble. The

Fig. 24

Pressure History of SWAT-3
Run-6 at P1113 ($\Lambda = 2.6$,
 $B = 0.65$, $W = 20.68$)-- Effects
of Λ

Fig. 25
Pressure History of SWAT-3
Run-6 at P1113 ($\Lambda = 2.6$,
 $B = 0.65$, $W = 20.68$) --
Effects of Varied Early
Leak Rate

Fig. 26

Pressure History of SWAT-3
Run-6 at P1113 ($\Lambda = 2.6$,
 $B = 0.65$, $W = 20.68$)-- Effects
of Combined Λ and Early
Leak Rate

break flow is usually a choked flow, and the pressure of the reaction bubble is below the critical pressure at the break.

The result of this work indicated that it was not possible to determine the early time-dependent leak rate sufficiently accurately to perform a critical validation of the reaction dynamics. Validation of the third part of the SWAAM-I code was limited to the shell-side locations near the reaction vessel due to the presence of the noncondensable gas bubbles in the piping. The drastic change in the compressibility due to the small amount of noncondensable gas in sodium makes the quantitative validation quite difficult. The results of analyses discussed in this report indicate that the early leak rate could have deviated as much as 50% (either way) from the measured quasi-steady leak rate. Furthermore, the reaction-rate modeling parameter Λ could assume a single value around $\Lambda = 5.0$ ft/sec for a wide range of steam-generator sizes and designs of internal tubes. It is then the conclusion of this report that the value of SWAT-3 data as the data base for validation of analysis computer codes cannot be fully utilized until the early leak rate can be determined with a reasonably high accuracy. The main difficulty in calculating the water-side blowdown transient was the lack of information on the initial conditions at the end of the filling flow transients. Since the initial conditions cannot be measured with sufficient accuracy, they must be calculated. Calculation of the filling flow transients must therefore precede any future validation of computer codes that may be undertaken with SWAT-3 data.

Once an accurate early leak rate is determined, the rest of the code capabilities can be easily validated. The helical-coil-design steam-generator unit has much greater three-dimensionality than the straight-tube design with a long L/D ratio. SWAAM-I models the steam-generator unit as a sectionwise one-dimensional pipe, and there is no well-defined method to develop the one-dimensional system model. SWAT-3 data can serve as a basis for verifying the validity of the one-dimensional modeling of the steam-generator unit. Moreover, the important design information regarding the fluid loading on the internal structures (such as the tube supports, shroud, etc.) can be derived, and one-dimensional lumped-parameter methods for modeling of such detailed fluid loading can be validated by the SWAT-3 data. The first attempt to develop the one-dimensional SWAAM-I models to obtain the detailed fluid forces on internals was made by Babcock and Wilcox [5]. However, no quantitative validation of the model could be made, because of the large potential uncertainty existing in the calculated leak rates.

APPENDIX A

Analytical Basis for Modeling of Tee Junction and Tee-Break Boundary

A tee junction is an internal boundary in which the waves from three connecting pipes interact. The water-side module of SWAAM-I uses the hybrid method of computation in which the interior flow is calculated by a finite-difference technique, while the boundary points are calculated by a new method based on the method of characteristics [8]. The use of the method of characteristics is a convenient means for computing boundary values, since the physical boundary conditions derivable from a given problem are not always translatable to the form necessary for the numerical scheme used. The method of characteristics maintains a close relationship between the physical phenomena and the numerical scheme, and is a suitable method for treating the boundary conditions. The new method developed for SWAAM-I is a semianalytical boundary method by which accurate boundary values can be obtained by a substep numerical integration. (See Reference [8] for details of the boundary method.) Accurate calculation of boundary values is often necessary for a stable calculation, because the large errors possible near the saturation lines, for example, can cause a complete breakdown of the numerical scheme. The large errors near the saturation lines are due to the steep changes in the state variables.

The same basic boundary method is used for the tee-junction treatment. The three-way wave-interaction diagram is shown in Fig. A-1. Pipes L_1 and L_2 have the inflow configuration; L_3 has the outflow configuration. The two material characteristics are first integrated (explicitly) to obtain the entropy at the new time step. Once the entropy at the boundary is obtained, the remaining task is to compute the remaining two variables, namely, the pressures and velocities for the three connecting pipes. Solution for the six unknowns requires six equations: three characteristic equations, two energy relations, and the continuity equation. Simultaneous solution of these six nonlinear equations in a closed form is impossible, especially when a substep integration is to be performed. Instead, a numerical procedure based on the substep marching technique is used. Figure A-2 describes the procedure schematically. The solution states for the three pipes must lie on their respective characteristics passing through their respective neighboring states. The neighboring states are R_1 , R_2 , and S for the two upstream pipes and the downstream pipe, respectively. Starting from an appropriately chosen state, state S for example, incremental changes of pressure are made along the S -characteristic, and the energy lines passing through that line are drawn. For each energy line drawn, a check is made whether the intercepts P_1 , P_2 , and P (intercepts of the energy line with the three characteristics) satisfy the continuity equation. The particular intercepts P_1 , P_2 , and P are the solution states of the pipes L_1 , L_2 , and L_3 , respectively. The states P_1 , P_2 , and P thus satisfy all six relations for the tee junction. In the process of marching, one of the three branches of the pipes can choke (local sonic condition). In this case, the flow decouples and the energy relation applies only to the remaining branches of pipes. An example of pipe L_2 choking is described in Fig. A-3. Here P_2 is the choked-state solution for pipe L_2 . Theoretically, any combinations of the three pipes can choke. There are, in all, eight different combinations.

(a) PHYSICAL CONFIGURATION

Fig. A-1
Tee-Junction Flow

(b) WAVE DIAGRAM

Fig. A-2
Tee-Junction Methodology--
Subsonic Solution

The tee-break boundary model is a break model to simulate the SWAT-3 rupture sleeve. The flows in the two branches of the pipe across the break location can continue interaction during the leak. The flows in the branches are also controlled by the break flow through the rupture-sleeve holes. This leak arrangement can best be modeled as a special tee junction, called here a tee-break boundary. The third pipe, L3, in the regular tee-junction configuration is no longer present. Instead, L3 is replaced by a break boundary. The flow configuration is shown in Fig. A-4. As shown in the solution-methodology schematic, Fig. A-5, the S-characteristic is no longer available. The boundary conditions are either the sonic line or the exhaust pressure line, and these are used in place of the S-characteristic.

(a) PHYSICAL CONFIGURATION

Fig. A-3. Tee-Junction Methodology--
Choked Flow Solution

(b) WAVE DIAGRAM

Fig. A-4. Tee-Break Bound-
ary Flow Fig. A-5. Tee-Break Bound-
ary Methodology

APPENDIX B

SWAT-3 Run-6 Data for Water-Injection-System Response

A number of valuable measurements were made of the water-injection system that could be used for verification of the analysis of both the initial filling transient and the subsequent blowdown. Because of the additional SWAAM-I capabilities needed to perform rigorous analyses of the filling transient as discussed in Sec. III, the initial conditions for the blowdown leak calculations were estimated from the SWAT-3 data and later refined by numerical experimentation. For the purpose of estimating the initial conditions, as well as for future use of the test data, the pertinent data are extracted from the SWAT-3 Run-6 Test Report [6] and reproduced here. A brief qualitative discussion is made here.

The water-heater tank and the main water-injection pipeline (pipeline from the water-heater tank to the branching point) are the parts of the system that contain the most mass inventory. Only a small mass of water/steam would be present in the small tubings below the branching point, as compared to the mass contained upstream of the branching point, in the large-size pipes and the water-heater tank. For this reason, more severe and longer transients would be present in the small-size tubings than in the large-size pipes. These are demonstrated in the data shown in Figs. B-1 through B-9. Water-heated condition changes only quasi-statistically. It is obvious that the condition can be treated as a constant reservoir condition for a short initial transient for less than 1 sec. The response of the large-size pipes is shown in Figs. B-2 through B-4. It appears that the pressure and flow histories both indicate that the condition approaches a quasi steady-state in about 200-300 msec. The report [6] indicates that the rupture disc (RD-501) opened at 65 msec after the main valve opening and the rupture sleeve broke at 153 msec. This implies that the blowdown phase of the transient settles to the quasi-steady state in a matter of 50-150 msec. The flow measurements of the turbine flowmeter and the drag disc show a transient response time of about 200 msec.

A number of pressure-transducer readings were made in the helical-coil section of the heat-transfer tubing (downstream of the branching point of the water-injection system). The transducer locations and the leak are indicated in Fig. B-5; the pressure histories are given in Figs. B-6 and B-7. These indicate that the blowdown transients persist for about 300 msec. The pressure distributions along the tubing at different transient times are plotted in Fig. B-8. The plot indicates that the pressure ranges from about 1140 to 1490 psia (80 to 105 kg/cm²) at the time of the rupture-sleeve break. A significant nonuniformity of pressure exists. These pressures are significantly lower than the water-heater pressure 2190 psia (154 kg/cm²).

Finally, the thermocouple readings are shown in Fig. B-9. Although a quantitative assessment does not appear very meaningful, it does appear that the temperatures during the early time (up to about 1 sec) were much above the saturation temperatures. In fact, the early temperatures appear to be much closer to the sodium temperature. (Note that the initial sodium temperature is greater than the initial water-tank temperature by about 250°F (140°C).) This indicates that a significant heat transfer took place

Fig. B-1
History of Water-Heater Conditions

Fig. B-2
Pressure Transient in Water-
Injection Pipe (P 5001)

Fig. B-3
Measured Result of
Turbine Flowmeter

Fig. B-4
Measured Result of Drag Disc

Figure 1 consists of three vertically stacked plots showing pressure versus time for three different test cases: PK 5001, PK 5002, and PK 5003. The y-axis for all plots is Pressure (kg/cm²) ranging from 0 to 150. The x-axis for all plots is Time [msec] ranging from 0 to 300. The plots show a sharp increase in pressure starting around 120 msec, peaking at approximately 200 msec, and then dropping sharply. The peak pressures are approximately 100 kg/cm² for PK 5001, 75 kg/cm² for PK 5002, and 60 kg/cm² for PK 5003. The pressure remains relatively stable after the initial drop, with a slight increase observed after 250 msec.

Fig. B-6 (Contd.)

Fig. B-6. Short-Time Pressure Transient in Water-Injection Tube

Fig. B-7. Long-Time Pressure Transient in Water-Injection Tube

Fig. B-7 (Contd.)

Fig. B-8. Pressure Distribution in Water-Injection Tube

Fig. B-9
Temperature in Water-Injection
Tube

Fig. B-9 (Contd.)

from sodium to water and a much higher enthalpy conditions of water/steam would exist as the initial conditions for the blowdown transient.

ACKNOWLEDGMENTS

We would like to thank Beverly Sha, who helped with generating the many SWAAM-I computer runs and reducing the outputs in various graphical forms. Appreciation is due to Max Weber, who performed the technical editing of the draft manuscript. Finally, we thank Emma Berrill for typing the final manuscript and proofreading the report.

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