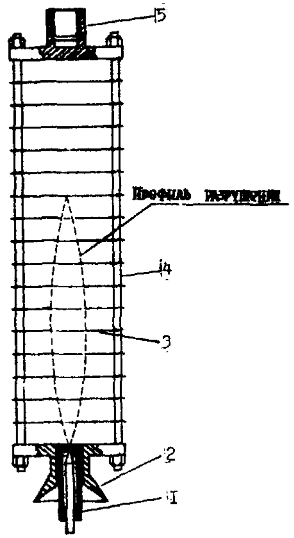

Рис. 7. Сборка мишеней: I–сопло; 2–направляющая втулка; 3–тонкая мишень; 4–стойка; 5–узел крепления

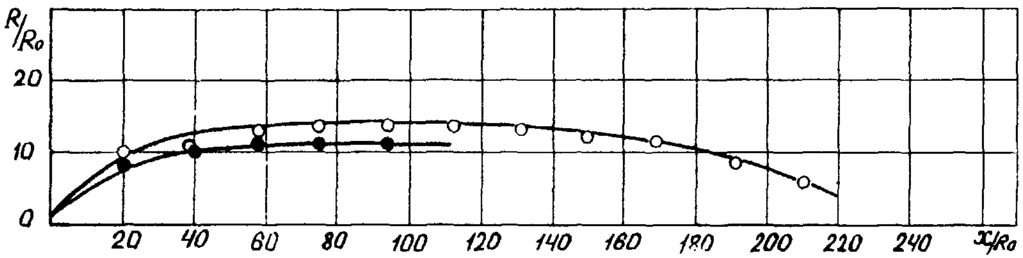

Рис. 8. Форма профиля разрушения в зависимости от материала мишеней: ● –сталь IХI8НI0Т; ○ –сталь 3

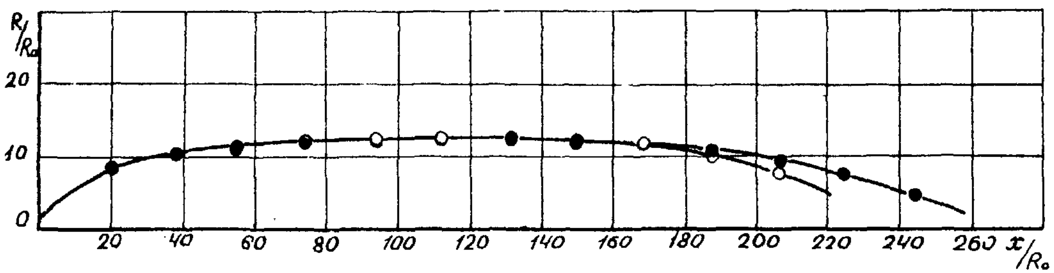

Рис. 9. Профиль разрушения мишеней в зависимости от времени подачи пара: ● – =6Iсек; ○ – =49,5сек

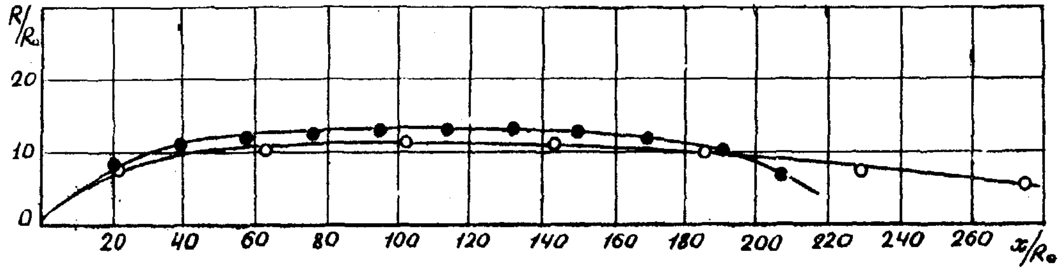

Рис.I0. Профиль разрушения в зависимости от расстояния между мишенями: ● – h =5I мм; ○ – h =II,6 мм

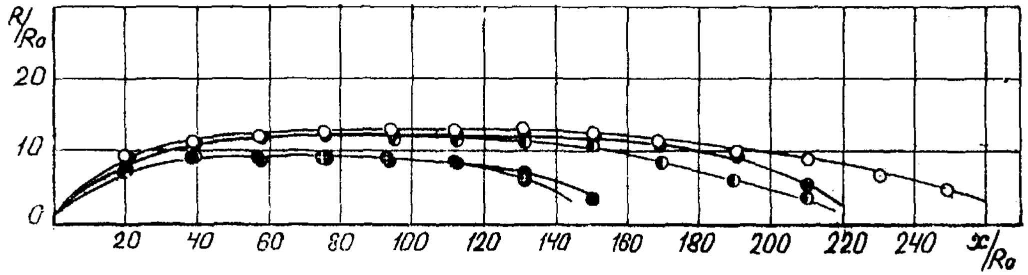

Рис. II. Влияние начальной температуры натрия на профиль разрушения: ◐ – t = 360°C; ● – t =390°C; ◐ – t =455°C; ● – t =500°C; ○ – t =600°C

C.8. Small Water/Steam Leaks in Sodium Heated Steam Generators: - evaluation of the Reaction Zone - effects on 2 ¼ Cr 1 Mo structural material

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Abstract:

On the basis of experimental data the geometry of a small leak reaction zone can be predicted for given leak sizes and steam generator operation conditions.

The effects of small leaks on 2 1/4 Cr 1 Mo material have been studied and completed with test results from foreign investigators. The results have to be considered as preliminary ones which have to be further qualified by additional information

1. Introduction

When discussing the effects of small water/steam leaks in sodium heated steam generators the expression "flame type reaction zone" is always used. In order to predict the influence range of such a reaction zone, a possibility of determining the size of the "reaction flame", would be very helpful in steam generator design and operation. In the literature concerning small leak tests a lot of more or less singular results are available. With regard to the reaction flame a special note should be made of the publications of Chamberlain [1], Masanov [2], Ueno [3] and Newman [4]. Furthermore, in order to control the validity of an empirically established flame description all available wastage data derived from different information can be used. All these wastage data which are completed by some results gained at INTERATOM have been generalised so that greater understanding of the flame effects of the 2 1/4 Cr 1 Mo steam generator material can be attained. As far as wastage is concerned the reported values of Chamberlain [1], Covacic [5] and Lions [6] together with INTERATOM test results were the main sources of information.

2. Empirical description of a flame model

During the last Specialists' Meeting on sodium-water reactions which was held at Melekess in 1971 the relationship between wastage area and leak size or leak distance was reported on by Masanov [2]. These results were assumed to be the negative of a reaction flame under the given test conditions (see Fig. 1).
At the same meeting Ueno [3] reported on simulation tests in which superheated steam was injected into comparatively cold water. The amount of superheat and the steam pressure were varied; the shape of the steam jet was observed and evaluated empirically. Besides the influence of superheat the relationship between steam pressure and jet length was found to be

$$H_{o}/d_{L} \triangleq \Delta p^{0,44} \qquad (1)$$

In accordance with normally used formulae describing flow rates the equation of Ueno was changed to

$$H_{o}/d_{L} \triangleq p^{0,5} \qquad (2)$$

The curve of Masanov can be described and extrapolated by the expression

$$d_{s}/d_{L} = 0,75 \cdot \frac{H}{d_L} - 0,008 \left(\frac{H}{d_L}\right)^2 \qquad (3)$$

The maximum flame length can then by the combination of (2) and (3) be evaluated to

$$H_o = 9,3 \cdot d_L \cdot \Delta p^{0,5} \qquad (4)$$

Equation (4) is shown graphically in Fig. 2. A more detailed impression is given in Fig. 3 where the ranges of flames with different leak sizes are plotted into the tube configurations of the SNR steam generators. Considering only small leaks of up to 0,5 mm in diameter it can be assumed that steam will always enter the sodium.. This is due to the combination of normal operating conditions and fairly high pressure drops in the leak penetrating the tube wall. Furthermore it is assumed that the injected steam has the same temperature as the surrounding sodium.

In the preheater and evaporator region the effective pressure difference is defined as being:

$$\Delta p = p_{sat} - p_{Na} \qquad (5)$$

The expression p_{sat} is defined as being the saturation steam pressure at the corresponding sodium temperature. For the calculation of leak rates the specific volumes and adiabatic exponents must be in agreement with this saturated conditions.

In the light of these assumptions equation (4) has been checked on available wastage tests and temperature measurements in order to determine the leak size below which wastage should no longer take place. The results of these checks show the satisfactory validity of the equation as given, for instance, in the Figures 8 and 9 where the corresponding leak rates q_o are marked.

Based on additional information on surface and reaction temperatures /¯1, 2, 4_7 which could be confirmed to a large extent by INTERATOM tests, a general picture of a reacting steam jet in sodium has been established (see Fig. 4):

A steam jet enters the sodium forming a flame type reaction zone. The reaction mainly takes place in a boundary mixing zone of approximately 1 mm thickness. The maximum temperature of this flame amounts to 1300 - 1500°C. The wall temperature in the affected region reaches values of up to 1000 - 1200°C. These values were also observed by direct temperature measurement as well as by metallurgical post-examinations of test specimens during INTERATOM tests.

By the reaction

$$Na + H_2O_{(g)} \longrightarrow NaOH + 1/2\ H_2 - 45\ kcal/mol$$

particles of sodium hydroxide are formed. The vaporisation temperature of NaOH is reported as being 1390°C /¯7_7, a temperature which is consistent with the measured temperatures. These particles impinge on the surface of an adjacent tube wall at velocities of about 100 m/s. The process of wastage can then be divided into different mechanisms.

- The adjacent wall is heated up by the reaction products affecting it.
- At high temperature and high concentrations of NaOH corrosion takes place.
- The corroded surface immediately becomes eroded by the impinging NaOH droplets; by this the corrosion process is maintained all the time on a clean and unprotected surface.

In order to avoid secondary damage through those processes it is necessary to detect a leak before it is able to produce a flame of a length larger than the free spacing of steam generator tubes.

3. INTERATOM wastage tests

INTERATOM has designed and constructed a special test facility for safety experiments in order to deal with all the problems associated with sodium-water reactions in LMFBR steam generators and other safety considerations. Figure 5 shows a flow scheme of this system:

Individual test sections are connected to a main sodium loop, designed for a maximum flow rate of 120 m^3/h. The pressurized water for Na-H_2O reactions is supplied by the high pressure water tank 10 in which even super critical steam conditions can be simulated by appropriately adjusting the pressure and temperature. Two test sections 12 are available for small leak experiments. Section 8 is the installation for steam generator models which are used for large leak tests. Sodium and sodium oxides ejected by the reaction are separated in a cyclone system from the hydrogen and the escaping steam, which are released to the atmosphere. Leak detection systems are tested in conjunction with the small leak experiments. These systems are located at the section 6 and 9, where 9 also serves for endurance tests. The loop is completed by a sodium boiling test section 7 for tests of core safety instrumentations.
Two different test sections have been used for small leak tests (see Fig. 6). One of them was used for examining the effects on flat plates; in this section surface temperature measurements were also performed. In the second test section pressurized tubes were used as target material. Compared with steam generator tubes

the target tube diameter was increased to reach a higher probability of hitting the target. The wall thickness of these tubes was kept equal to those of the steam generators and the internal pressure adjusted to produce the same stress as 180 bar steam pressure in a steam generator tube. The leaks were simulated by two different injection arrangements as shown in Fig.7. The leak arrangement consists of a small austenitic capillary tube brazed into a mounting support and closed by a small rupture disc. This rupture disc is either actuated directly by the steam pressure or by a moving piston. In order to avoid water side blockage small sinter metal filters are inserted.

The Figures 8 and 9 show results of wastage tests on flat plates and tubes using 2 1/4 Cr 1 Mo ferritic steel as target material. The test conditions are given in the diagrams. Evaluating the test results, three different patterns of secondary damage could be observed as schematically shown in Fig. 10.

case a: (solely for the sake of completion) the flame is shorter than the free distance between the tubes, secondary damage cannot occur.

case b: the flame touches the adjacent wall, a cone shaped locally concentrated wastage will arise. Wastage tests under such conditions are sufficiently well reproducible.

case c: the flame becomes larger; the core of the flame containing still unreacted steam hits the surface of the adjacent tube. The wastage pattern changes into a toroidal shape. The bulge in the center is due to the lower corrosion and erosion in the steam jet core. Results of this type are marked with T in Figures 8 and 9. The reproducibility is not as good as in case b.

case d: the flame increases further. The toroidal wastage is reduced. A continuous reaction takes place on the tube surface. The tube is heated up to an extent that it becomes buckled due to internal pressure. The quality of reproducibility is extremely low.

A lot of tube tests were run in which wastage was produced until the tube failed due to internal pressure. It could be demonstrated that in the cases b and c, 85 to 90 % of the nominal wall thickness can be removed before a secondary leak occurs. These values are in complete agreement with results reported by Russian and American specialists /¯2, 8_7.

4. Compilation and generalization of wastage test results

Wastage rates are normally plotted against leak rate. Based on the flame model, described in chapter 2, and the assumptions made in order to describe the effective pressure difference Δp the leak rates were transformed into equivalent leak sizes d_L.
Introducing the target distance H the leak rate is replaced by the

relative distance $\frac{H}{d_L}$

Supported by the work of Masanov /¯2_7 it was assumed further that similar wastage will take place at similar $\frac{H}{d_L}$ - values. Available wastage test results are gained at very different pressure differences Δp. In order to generalize them to a given steam pressure p_o the $\frac{H}{d_L}$ values wer transfered into

$$\left(\frac{H}{d_L}\right)_{p_o} = \left(\frac{H}{d_L}\right)_{\Delta p} \cdot \left(\frac{p_o}{\Delta p}\right)^{0,5} \qquad (6)$$

The square root dependency is due to equation (4). A diagram in which the wastage rates are plotted against the relative distance at p_o shows the strong influence on sodium flow velocity.
(It should be mentioned that a possible influence of sodium temperature on wastage is neglected).

Finally it was assumed that for different velocities the ratio of the relative distances should be constant over the whole range of wastage.

$$(\frac{H}{d_L})_{v_1} : (\frac{H}{d_L})_{v_2} \cdots : (\frac{H}{d_L})_{v_n} = \text{const.} \qquad (7)$$

The result of a generalization of wastage data for a steam pressure p_o of 170 bar is depicted in Fig. 11.

The velocity parameters are given as velocity ranges, as given by the reported data. A generalization for specific velocities was not possible. This might be due to uncertainties in flow measurement. Normally the flow is measured at the inlet of a test section and the velocity is calculated by taking the nominal cross section into account. In how far the flow distribution in a test section is influenced by the reaction itself is unknown and may even depend on the configuration of the test section.

According to / 2 / and case d of wastage pattern the curves are limited to start at about $\frac{H}{d_L} > 15$. The theoretical maximum of $\frac{H}{d_L}$ is controlled by the flame length i.e. the steam pressure.

5. Final remarks

Status of the art for the detection of a small leak in a steam generator is the use of hydrogen detectors with nickel membranes. The response time of such systems is strongly influenced by the transport time of the hydrogen. Strong dependency of wastage rates on flow velocity would lead to the fact that for a given leak size wastage and detection time would be in contradiction.

Leak detection requirements have to take these phenomena into account. Details on this point are given in a separate paper /‾9_7 and in literature /‾10_7.

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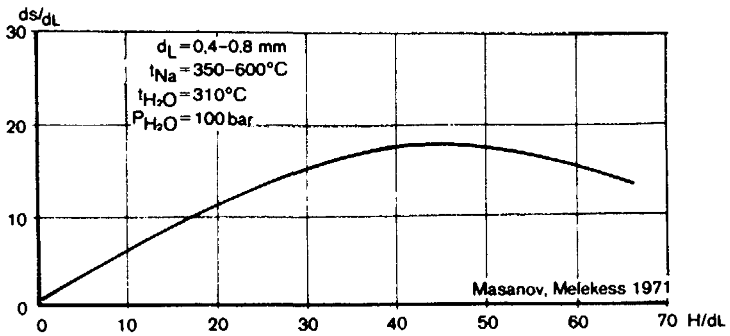
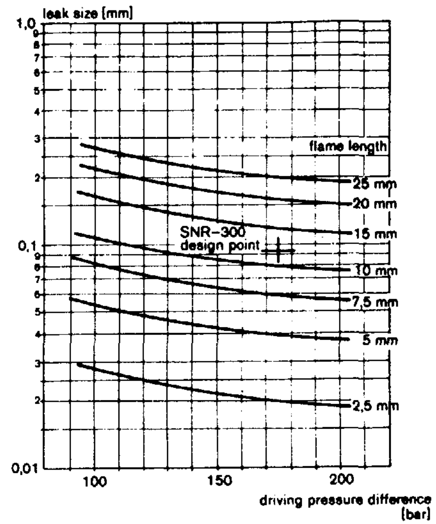


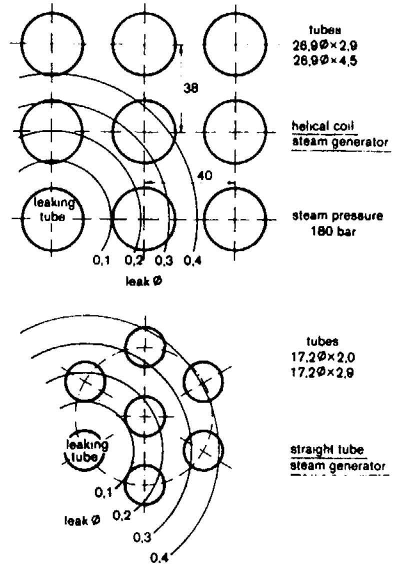
ASSUMED SHAPE OF REACTION FLAME

FIG. 1



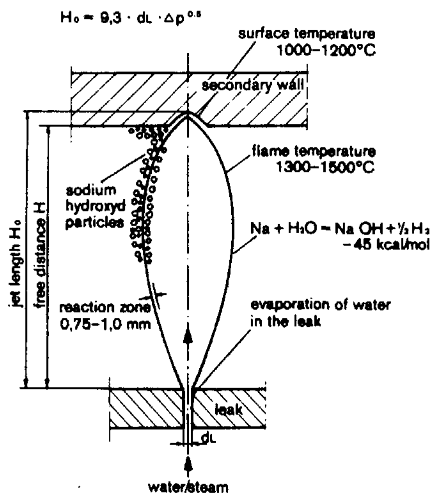
RADIUS OF INFLUENCE OF STEAM JETS IN SODIUM

FIG. 2.



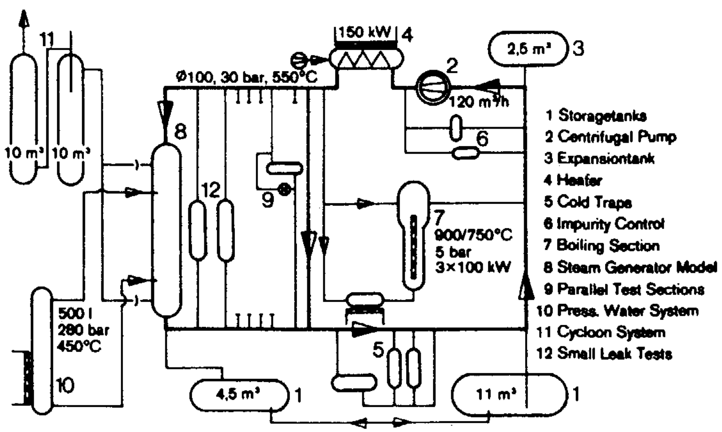
FLAME INFLUENCED REGIONS IN DIFFERENT TUBE ARRANGEMENTS

FIG. 3.



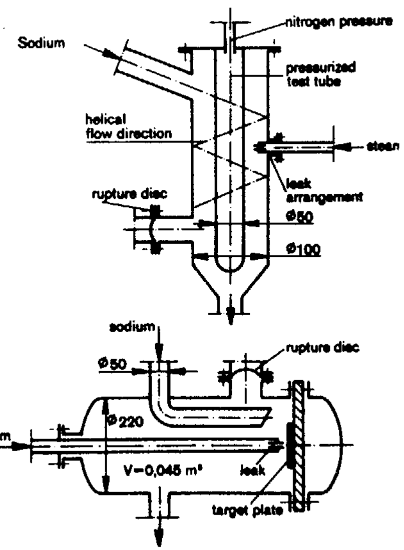
MODEL OF REACTION FLAME

FIG. 4.



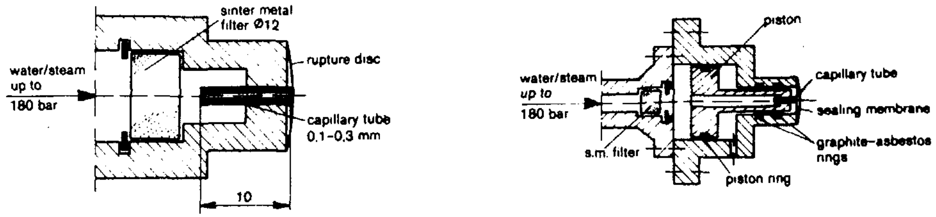
ASB FLOW SCHEME

FIG. 5.



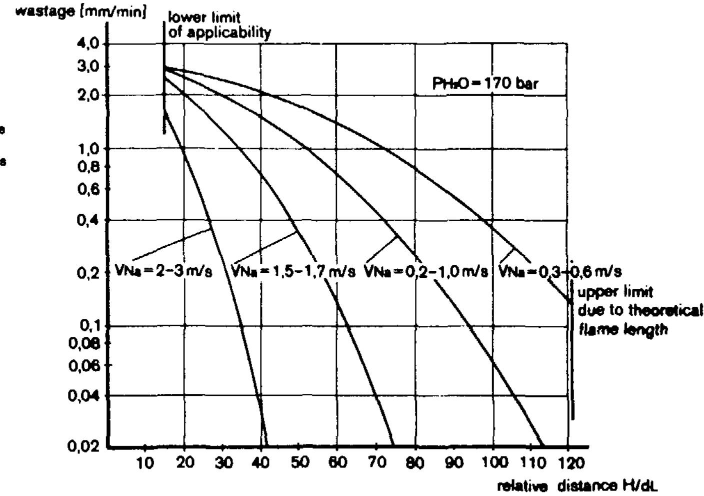
PINHOLE TEST SECTIONS

FIG. 6.



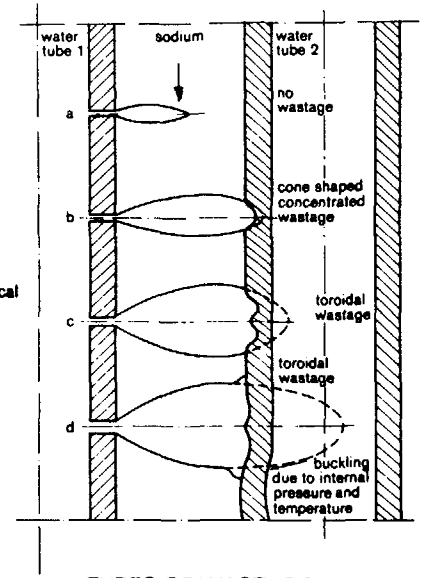
PINHOLE INJECTION SYSTEMS

FIG. 7.



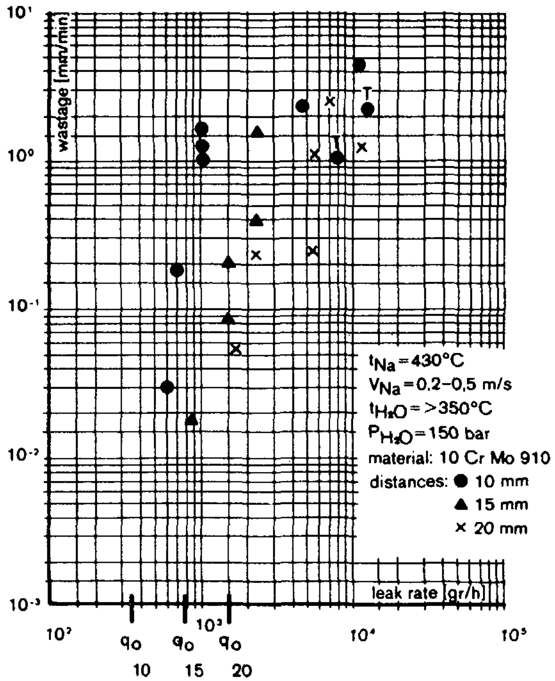
WASTAGE RATES AT DIFFERENT SODIUM VELOCITIES

FIG. 10.



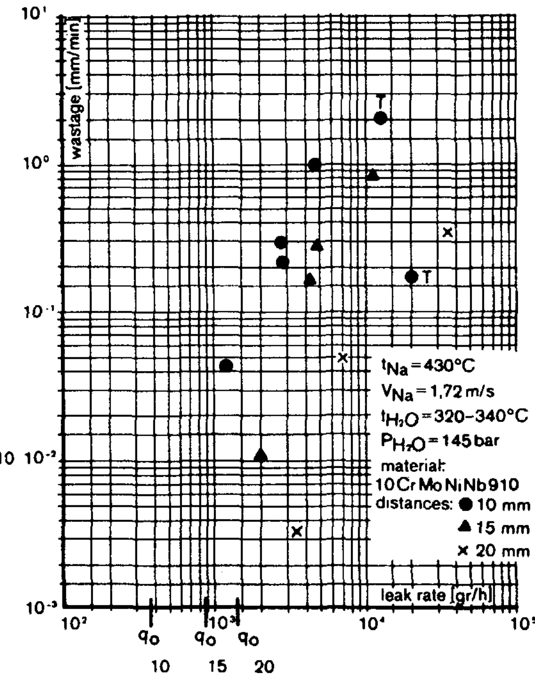
TYPES OF WASTAGE

FIG. 11.



WASTAGE TESTS ON FLAT PLATES

FIG. 8.



WASTAGE TESTS ON PRESSURIZED TUBES

FIG. 9.

C.9. **Metallurgical Examination of Wastage Materials**

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2. Experiment

A series of tests on small leak steam-sodium reaction was conducted by the use of PNC's SWAT-2 loop. Tests were conducted under the following conditions:

Sodium velocity	0.24 m/sec
Nozzle-target spacing	17.5 mm
Injection direction	vertical
Target tube diameter	26.5 mm

The other conditions and wastage data are summarized in Table 1.

After cutting the tubes and nozzles, all cut surfaces of tubes and nozzles were degrased in acetone and alcohol. The samples for metallography and hardness tests were embodied in epoxy resin and were polished by commonly used polishing procedure. The etchants were 5% Nital for ferritic steel and glycerinated aqua regia for austenitic steel respectively.