Fatigue Rupture of Roofing Membranes at Joints in Roof Deck

Michio KOIKE*

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Abstract

Twelve types of roofing membranes were tested by tentative test methods for the purpose of evaluating their ability to withstand movements which take place in roof decks. Two types of vulcanized rubber sheetings showed very good resistance to movements. They might be, however, weak in resistance to ozone in the atmosphere under tensile strain. Thus, the application of vulcanized rubber sheeting should be determined in accordance with ozone resistance. Two types of plasticized polyvinylchloride sheetings withstood the movement from 0 to 1.0 mm. It is advisable to apply asphaltic membranes and fluid-applied synthetic membranes to the roofs where movements as small as 0.5 mm are expected to take place. Two of these are so weak to movements that they should be applied only to the roofs where almost no movements are expected. Since the ability for the membranes to withstand the movements in the roof deck is very important, establishment of standard test methods is an urgent necessity for improvement of roofing membranes.

Introduction

Over the past ten years, Dr. M. Hamada, professor emeritus, University of Tokyo, other professors and the author have been greatly interested in roof coverings made of asphalt and other materials[1),2)]. The first systematic leakage inspection of asphalt roofing membranes was made in 1957, and breakages in the membranes caused by crcaks in roof decks were often discovered[3)]. No mention in the literature had been made on these breakages up to that time, and the author and others considered that these breakages were serious failures of the membranes.

The author has been engaged in a study of roofing membranes thereafter, especially in the study of prevention of breakage in the roofing membranes caused by caracks or joints in the roof decks[4~9)]. At present, it is generally recognized in our country that breakage in the roofing membrane is one of the most leading causes for water leakage, usually a short time after the installation of the membrane[10~12)].

During the aforementioned study, the author found that repeated movements of the crack or joint in the roof deck were very harmful to membrane. All

* Assistant professor, Department of Architecture, Dr. of Engineering.

roofing membranes in any roof are subjected to weathering action in the atmosphere, and, more or less, they are also subjected to repeated movements of cracks or joints in the roof deck as well as of roof deck itself. Cracks and joints in the roof deck move because of temperature changes or vibration of the structure caused by heavy traffic or from the operation of the building itself. The occurance of this kind of movement is very harmful to the membrane. Even if the membrane is not ruptured by the movement, considerable strain may develope in the membrane. It is well known that some types of roofing materials, such as natural and synthetic rubbers, easily crack in the atmosphere under tensile strain. For this reason, the author recognized the necessity for fatigue rupture test for roofing membranes, and designed a testing apparatus in order to test membranes with various movements and under various temperature conditions.

In this paper, the results of fatigue rupture tests for twelve types of roofing membranes, in which membranes made of asphalt, synthetic resins and synthetic rubbers are contained, are reported. This paper integrates the author's previous paper published by the American Society for Testing and Materials[13], and the abbreviations of the test membranes were accordingly changed in this paper.

Roofing Membranes Tested and Test Specimens

Twelve types of roofing membranes which are generally used in our country were selected for the test. Four of them were asphaltic membranes, three were hot-applied 3-ply membranes and one was fluid-applied membrane reinforced with glass fiber woven cloth (Table 1). Properties of bonding and coating asphalt are shown in Table 2. The next four were fluid-applied synthetic membranes (Table 3); two types of neoprene/Hypalon systems, one was reinforced with mixed glass fiber and the other with poly fiber woven cloth, a neoprene/epoxy resin system reinforced with poly fiber woven cloth, and an acrylstyrene emulsion system reinforced with poly fiber

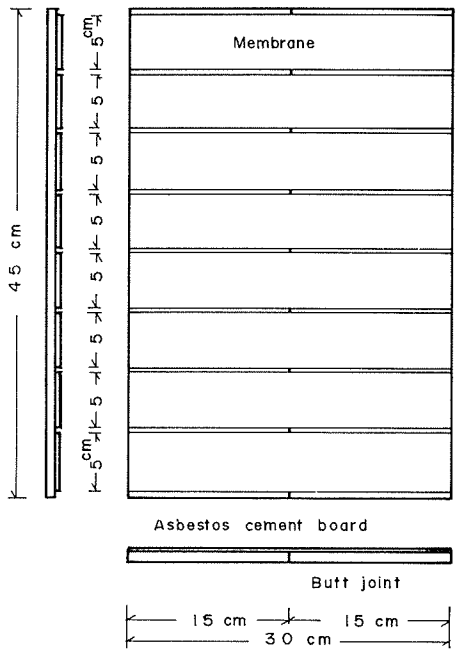


Fig. 1. Test specimen.

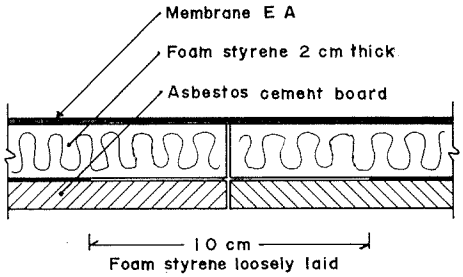


Fig. 2. The special substratum for relieving stress in Membrane EA.

Table 1. Specifications for asphaltic test membranes

Membranes	Compositions							
	1	2	3	4	5	6	7	8
RA	Asphalt primer (0.1 ℓ/m²)	Rubberized asphalt (1.5 kg/m²)	Asphalt-saturated felt (30 kg-Type)	Compounded blown asphalt (1.5 kg/m²)	Asphaft-saturated and coated felt (35 kg-Type)	Compounded blown asphalt (1.5 kg/m²)	Asphalt-saturated and coated felt (35 kg-Type)	Compounded blown asphalt (1.5 kg/m²)
OA	same as above	Compounded blown asphalt (1.5 kg/m²)	same as above	same as above	same as above	same as above	same as above	same as above
SA	same as above	same as above	same as above	same as above	Special roofing felt	same as above	same as above	same as above
EA	Fluid-applied membrane made with asphalt emulsion (3.5 ℓ/m²) reinforced with a layer of glass fiber woven cloth.							

Table 2. Properties of asphalts

Properties		Rubberized asphalt	Compounded blown asphalt
Softening point (R. & B.)	°C	111	77
Penetration	0°C, 200 g, 60 sec.	21	15
	25°C, 100 g, 5 sec.	42	26
	46°C, 50 g, 5 sec.	too soft	60
Ductility, cm	25°C	8.9	3.7
	0°C	4.5	0.6

Table 3. Specifications for fluid-applied synthetic test membranes

Membranes	Compositions
NH-1	Neoprene: 2.3 kg/m² (solid content—43%, color—brown, sp gr—1.28) reinforced with mixed glass fiber 12 g/m². Hypalon: 0.3 kg/m² (solid content—21%, color—white, sp gr—1.12).
NH-2	Neoprene: 1.5 kg/m² (solid content—35%, color—gray, sp gr—1.25) reinforced with one layer of poly (vinyl alcohol) fiber woven cloth (41 g/m²). Hypalon: 1.5 kg/m² (solid content—30%, color—white, sp gr—1.2).
NE	Neoprene: same as NH-2. Epoxy resin: 1.2 kg/m² (solid content—80%, color—silver, sp gr—1).
AS	Acrylstyrene emulsion: 1.1 kg/m² (solid content—50%, color—clear after dried, sp gr—1.1) reinforced with two layers of poly (vinyl alcohol) fiber nonwoven cloth (60 g/m²) and woven cloth (43 g/m², 22 by 22 mesh/in²).

Table 4. Specifications for elastic sheeting test membranes

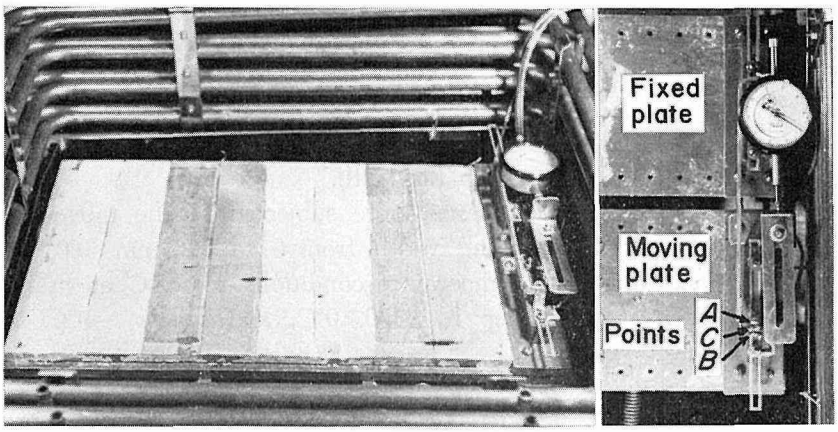
Membranes	Compositions
BR	Butyl rubber sheeting, 0.8 mm thick, bonded with neoprene adhesive.
NR	Neoprene rubber sheeting, 0.8 mm thick, bonded with neoprene adhesive.
VC-1	Plasticized polyvinylchloride, 2.5 mm thick, bonded with polyvinylacetate adhesive.
VC-2	Plasticized polyvinylchloride, 1.0 mm thick, bonded with polyvinylacetate adhesive.

woven and non-woven cloths. The last four were elastic sheetings (Table 4); a butyl rubber sheeting, a neoprene rubber sheeting, and two types of plasticized polyvinylchloride sheeting. All were bonded to the substratum with adhesives specified by the manufacturers.

The test membranes were installed on two plates of asbestos cement board so as to bridge over a butt joint formed between them. The specimens are shown in Fig. 1. As the fluid-applied asphaltic Membrane EA proved to be easily ruptured by movement in the previous test, a special substratum was provided only for Membrane EA for the purpose of relief of stress in the membrane (see Fig. 2).

Testing Apparatus

A tentative testing apparatus was designed and made. The apparatus consists of two parts. One is a movement tester which can cause repeated expansion and contraction of the butt joint in the specimen. Another is a constant-temperature box in which the movement tester is placed. It can be controlled at constant temperatures from −45°C to 100°C in the box (see Fig. 3, *left*). Operation of the tester is as follows: There are two plates at the upper parts of the tester,



(*left*) Specimen on movement tester in the constant-temperature box.
(*right*) Electric contact points.

Fig. 3. Testing apparatus.

one is a fixed plate and another is a moving plate that can travel horizontally at various speeds in the same plane with the fixed one. Two electric contact points, *A* and *B* of Fig. 3, *right*, are attached to the moving plate, and another point, *C*, is situated between points *A* and *B*. Point *C* is attached to the fixed plate.

Repeated movements are caused at the butt joint in the specimen, of which one side fixed to the moving plate and the other side to the fixed plate, as follows: The moving plate travels forward, and when point *C* comes in contact with point *A*, the motor which drives the plate stops and a timing relay starts to count an interval. After a fixed interval that is set in the timing relay, the motor reverses and the moving plate travels back. When point *C* comes in contact with *B*, the motor stops and, after the fixed interval that is set in the timing relay, it starts to drive the moving plate forward again. This repeated movement is continued.

The maximum width of the butt joint can be controlled by changing the distance between the contact points *A* and *B*. The period of one cycle of movement can also be controlled by changing the speed of the moving plate and the interval of the driving motor.

Test Methods

It is a very difficult problem to determine what the test conditions should be. There is no definite idea available concerning the extent of movement and the period of one cycle of movement. Although there are too many unknown factors for testing the membranes, some trial test conditons were decided upon for the first step of this undeveloped test. Considering the combinations of the amplitude of movements and temperatures, the author adopted the following three tentative methods in this paper. Method *A* was applied to all of the test

membranes, and Methods *B* and *C* were applied only to the fluid-applied synthetic membranes.

Test Method A

Six kinds of test conditions were successively given to the same specimen, following the series from the first to the sixth.

In the first series, the membranes were subjected to the movement of the butt joint in the specimen changing width from 0 to 0.25 mm (0.01 in.). This procedure was done under the temperature conditions of 20°C at first, then up to 60°C, then down step by step to 20°C, 0°C, and finally −5°C. At each

Table 5. Test program in Method A

Series	Movements	Steps / Temp. (°C)	1	2	3	4	5	6	7	8	9	10
			20	60	20	0	-5	-10	-15	-20	-25	-30
I	0 - 0.25 mm		○	→ ○	→ ○	→ ○	→ ○					
II	0 - 0.5 mm		○	→ ○	→ ○	→ ○	→ ○	→ ○				
III	0 - 1.0 mm		○	→ ○	→ ○	→ ○	→ ○	→ ○	→ ○			
IV	0 - 2.5 mm		○	→ ○	→ ○	→ ○	→ ○	→ ○	→ ○	→ ○		
V	0 - 5.0 mm		○	→ ○	→ ○	→ ○	→ ○	→ ○	→ ○	→ ○	→ ○	
VI	0 - 10.0 mm		○	→ ○	→ ○	→ ○	→ ○	→ ○	→ ○	→ ○	→ ○	→ ○

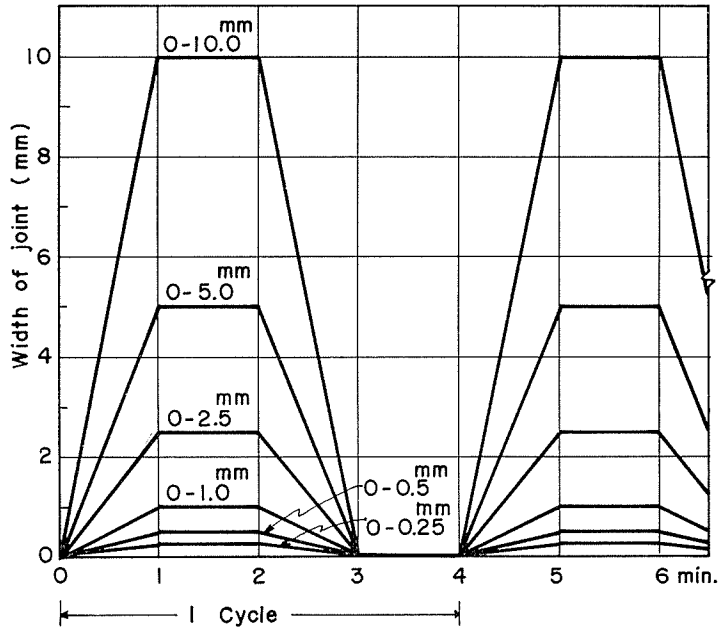


Fig. 4. Typical diagram of the movements.

temperature, movement was repeated 300 times in 20 hr. In the second series, the membranes which had been tested in the first series were tested with movements from 0 to 0.5 mm (0.02 in.), under the same temperature conditions as in the first series, and finally −10°C was added. In the third series, the membranes were successively tested with movements from 0 to 1.0 mm (0.04 in.) under the same temperature conditions as in the second series, and finally −15°C was added. In the fourth series, the test was continued with movements from 0 to 2.5 mm (0.1 in.) under the same temperature conditions as in the third series, and −20°C was added. In the fifth series, movements from 0 to 5.0 mm (0.2 in.) was given and −25°C was added. In the sixth final series, movements from 0 to 10.0 mm (0.4 in.) was given and −30°C was added. This test program is shown in Table 5, and movements were designed to follow the typical diagrams shown in Fig. 4. A stage during the test is expressed with a combination of series and step. For example, an abbreviation "II–3" means the stage when the test was made until Step 3 in Series II.

Test Method B

The test membranes were subjected to movments from 0 to 0.5 mm (0.02 in.) under the temperature conditions of 20°C at first, then up to 60°C, then down to 20°C again, and finally down to −20°C. At each temperature, movement was repeated 300 times in 20 hr. This procedure, called "one round" in this paper, was continued to the tenth round. Movement is shown in Fig. 4.

Test Method C

The same procedure as Method B was carried out, except that the movement was from 0 to 1.0 mm (0.04 in.), and was continued only to the fifth round. Movement is shown in Fig. 4.

Test Results and Discussion

The test membranes were inspected, and photographs of them were taken at every 300-cycle interval during the test. The test results made by Method A are shown in Fig. 5, and the results of fluid-applied synthetic membranes by Methods A, B and C are shown in Fig. 6. The defects developed in the membranes are progressively shown in Figs. 7 to 16.

1) As for Membrane RA, no notable defects were apparent until the stage "III–3" (4,200 cycles), and slight cracks appeared in the stage of "III–4" (4,500 cycles) in one specimen, but it did not thoroughly rupture until "III–7" (5,400 cycles) by Method A. In the other specimen, no notable defects were apparent until "III–7" (5,400 cycles). Membrane RA showed superior results to Membrane OA. This difference is probably due to the effect of rubberized asphalt which bonds the saturated felt to the substratum, because Membrane RA only differs from Membrane OA in this bonding material. As rubberized asphalt is more ductile than compounded blown asphalt, especially at low temperatures, i. e. ductility of the former at 0°C is 4.5 cm, on the other hand, that of the latter is only

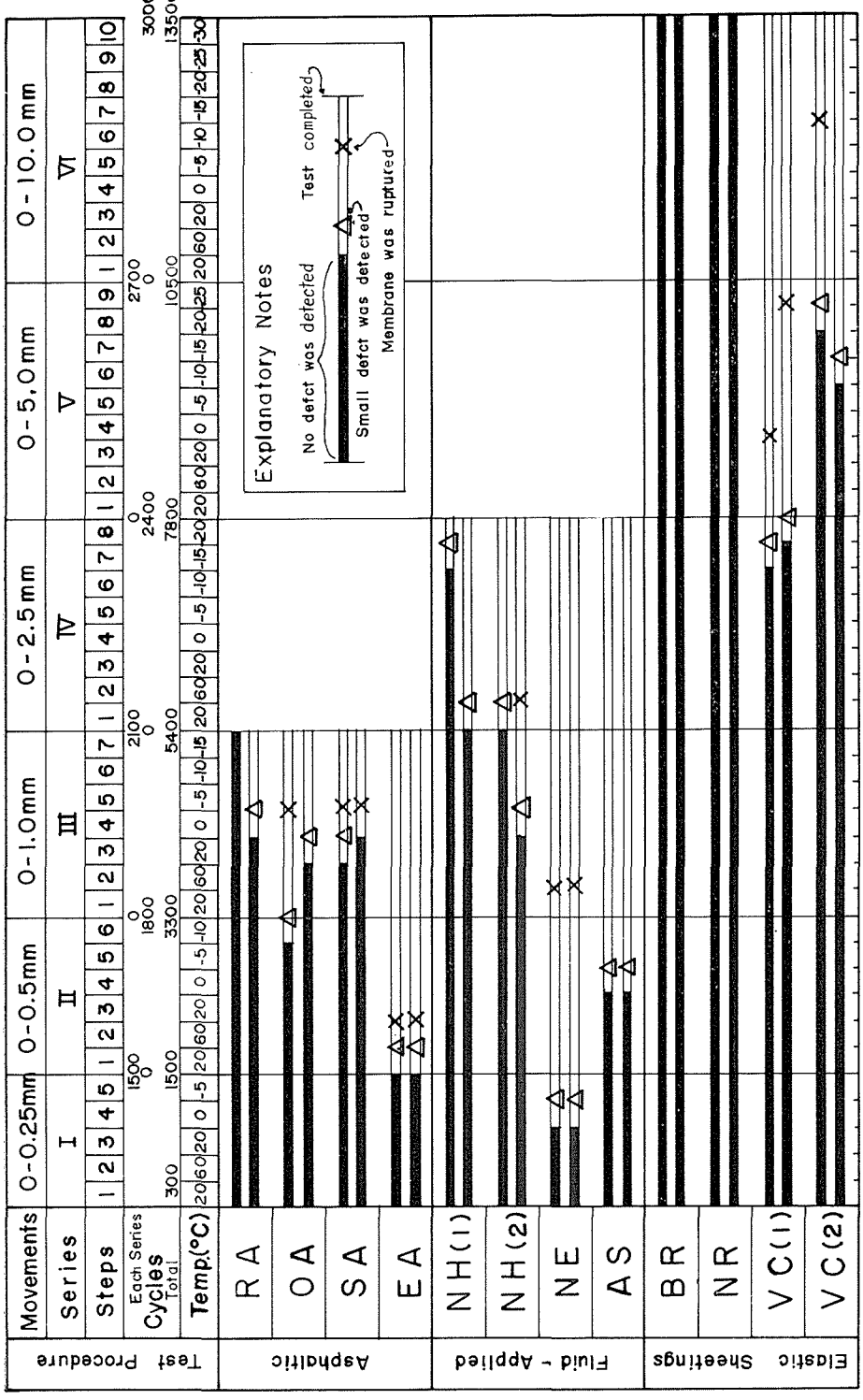


Fig. 5. Test results by Method A.

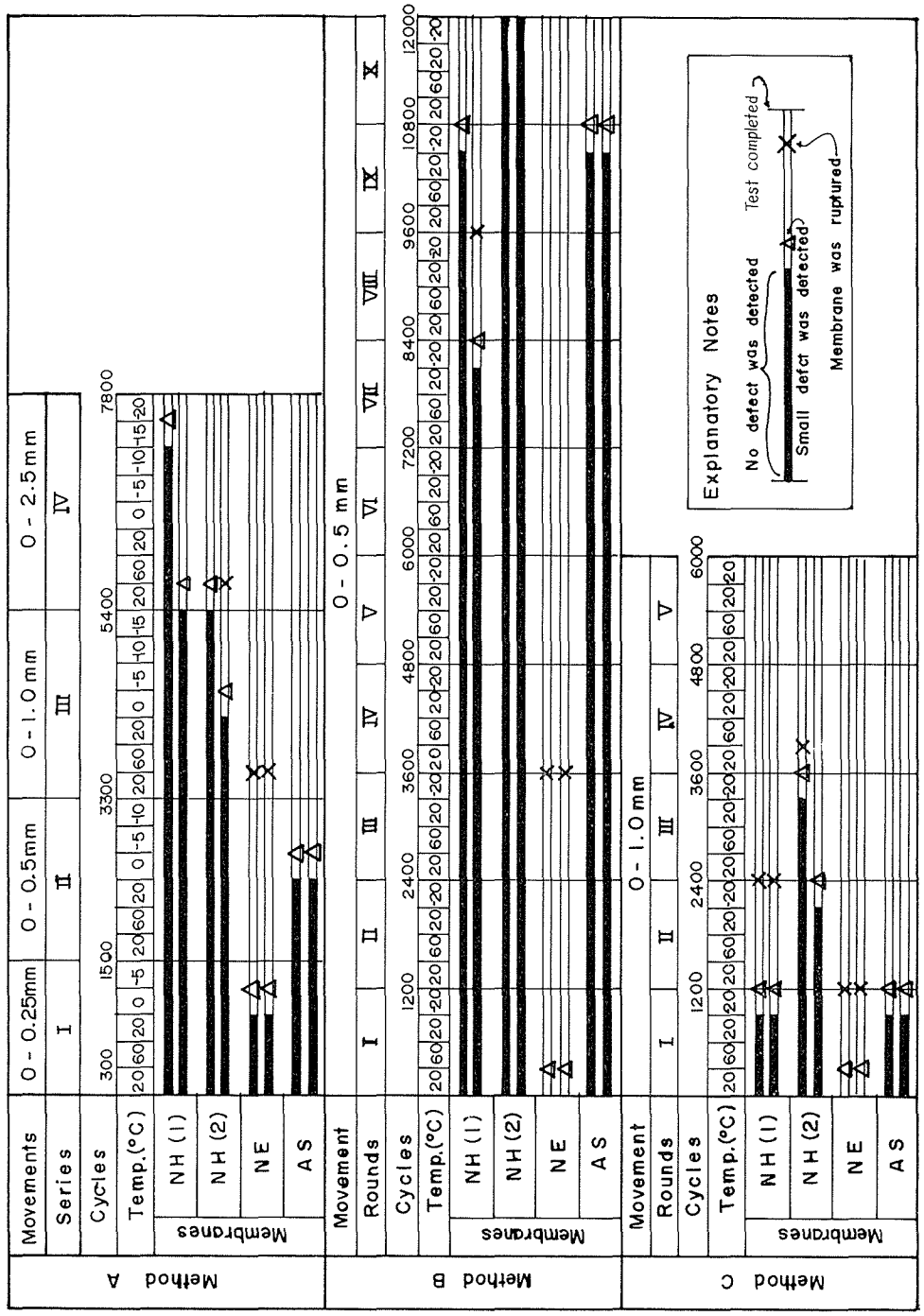


Fig. 6. Test results of fluid-applied synthetic membranes by Methods A, B and C.

0.6 cm, thus the stress which develops in Membrane RA shows a higher release of the stress than in Membrane OA.

2) As for Membrane OA, slight cracks appeared at "II-6" (3,300 cycles) in one specimen and at "III-3" (4,200 cycles) in the other, and they ruptured at "III-4" (4,500 cycles) and "III-7" (5,400 cycles) by Method A.

3) As for Membrane SA, slight cracks appeared at "III-3" (4,200 cycles) in one specimen and both specimens ruptured at "III-4" (4,500 cycles) by Method A. The special roofing felt used in Membrane SA is expected to improve mainly on water tightness and weather resistance of built-up membrane. However, SA is not improved, in its resistance to fatigue rupture caused by movement.

4) Since Membrane EA was easily ruptured by movement in the previous test, a special substratum was provided. Both of the specimens, however, ruptured in the early stage of "II-2" (2,100 cycles) by Method A.

5) As for Membrane NH-1, no notable defects were apparent until "III-7" (5,400 cycles) by Method A, and until 8,100 cycles by Method B. But defects appeared as early as 1,200 cycles of movement by Method C. Considering the result that Membrane NH-1 was not superior to Membrane NH-2 by Methods B and C, the expected reinforcing effect of mixed glass fiber in NH-1 might be insufficient. The manufacturer of materials for NH-1 twice revised the amount of mixed glass fiber, and later on, adopted woven cloth reinforcing as in the case of Membrane NH-2.

6) As for Membrane NH-2, it showed superior results to NH-1 by Methods B and C. Especially by Method B, no remarkable defects except wrinkling were noticed during the entire test period up to 12,000 cycles.

7) Membrane NE showed the worst results in all tests except for Membrane EA. This was anticipated before the tests. Membrane NE seemed to be useful, not as a roof covering, but as a chemical resistant coating in reservoirs and in places where chemical resistance was important. Contrary to the author's expectations, however, it did not withstand movement even as small as 0.25 mm, which in a minimal requirement for all roof coverings and coatings for concrete structures.

8) In Membrane AS, defects appeared at first in the upper layer which was reinforced with woven cloth. The reinforcing effect with woven cloth seemed to be less satisfactory than with non-woven cloth in this membrane. Although slight cracks appeared in the early stages in the tests, i.e. at "II-4" (2,700 cycles) by Method A, and After 1,200 cycles by Method C, Membrane AS did not throughly rupture when the tests were concluded. The reason may be as follows: when separation of the membrane from the substratum or between layers takes place, stress in the membrane developed by movement of the butt joint is relieved, and the membrane can withstand higher cycles of movement as compared against the case where almost no separation took place. Separation between layers reinforced with woven cloth and non-woven cloth seemed to take place in Membrane AS.

9) As for Membranes BR and NR, no notable defects were noticed after

"VI–10", in other words, when the whole test period up to 13,500 cycles concluded, by Method A. BR and NR showed a high durability to fatigue caused by repeated movement in this test. However, cracking of them is often induced by ozone in actual roofs. Ozone in the atmosphere tends to increase gradually, since it is thought to be formed by the action of sunlight on oxygen of the air in the presence of impurities, such as smog or exhaust gas from cars. The increase of ozone in the atmosphere is detrimental to vulcanized rubber sheetings. Therefore, the manufacturer of Membrane BR changed its constituent from butyl rubber to EPT (ethylene-propylene-terpolymer) blended with butyl rubber, which is more durable to ozone than pure butyl rubber, after about two years experience at actual building sites. And the manufacturer of Membrane NR is contemplating a change from neoprene rubber to EPT blended with butyl rubber. For these membranes made of vulcanized rubber, ozone cracking tests shonld be carried ont.

10) Membrane VC–1 was developed as a roofing membrane to provide waterproofing and resistance against weathering and light traffic. No notable defects were apparent until "IV–6" (7,200 cycles) and the base layer of the membrane, which consisted of two layers, i. e. the base layer and surface, was ruptured at "IV–7" (7,500 cycles) in one specimen and at "IV–8 (7,800 cycles) in the other by Method A. They were thoroughly ruptured at "V–3" (9,000 cycles) and "V–8" (10,200 cycles).

11) In Membrane VC–2, no apparent defects appeared until "V–5" (9,300 cycles), and slight cracking occured at "V–6" (9,600 cycles) and "V–8" (10,200 cycles) by Method A. thereafter, they ruptured at "V–9" (10,500 cylces) and "VI–6" (12,300 cycles).

12) Evaluation of the test membranes obtained in this test is as follows: The asphaltic Membranes OA and SA should be used on roofs where movements less than 0.5 mm are expected. Membrane RA has a slightly higher resistance to movement than Membranes OA and SA. These results are fairly in accordance with data obtained from actual roofing performance. Membrane EA should be applied only to small-scale roofs where almost no movements are expected, or where possible movements can be treated with other measures.

Fluid-applied synthetic Membranes NH–1, NH–2 and AS should only be used on roofs where movements less than 0.5 mm are expected. Membrane NE should be applied only to small-scale roofs, reservoirs etc. where almost on movements are expected, or where possible movements can be treated with other measures.

The vulcanized rubber sheeting Membranes BR and NR showed a superior resistance to movements. However, one should note that they have an inherent weakness in their resistance to ozone in the atmosphere nuder tensile strain. Membranes VC–1 and VC–2 showed fairly good resistance to movements. It is not advisable to bond them to roof decks with strong adhesives, since we have a case where tightly bonded Membrane VC–2 was ruptured by vibrations of railroad trains passing near the building.

13) The test methods adopted in this paper are only tentative ones. Test

conditions should be carefully determined by considering the climate where buildings are constructed and by calculating the movements that are expected to take place in the roof decks.

There are very difficult problems for testing roofing membranes. One is the lack of records of movements which take place in actual roof decks, except for a little knowledge obtained by the observation of roof decks constructed by several different methods. Another is that we have no knowledge about the relationship between the period of one test cycle of the movement and the damage in the membrane caused by the movement, if the amplitude of the movement is the same. The author ascertained a tendency in the asphaltic membranes in previous test that the shorter the period of test cycle, the harder the damage in the membrane.

The ability for roofing membranes to withstand movements in roof decks is important and the establishment of standard test methods is necessary for the improvement of roofing membranes.

Conclusion

The results obtained in this paper are in fairly good accordance with experiences in actual roofs, except for vulcanized rubber sheetings. Method A in this paper has a tendency, however, to show rather a large critical extent of movement than in actual service. It may be improved by increasing repetitions of movement in every step from 300 to 1000 cycles or more. Methods B and C are more suitable than A, but the disadvantage is that it requires several tests to determine the critical extent of movement.

Membranes EA and NE should be applied only to the roofs where almost no movements are expected, or where possible movements can be treated with other measures. Membranes OA, SA, RA, NH–1, NH–2 and AS should be applied to the roofs where movements of less than 0.5 mm are expected. Vulcanized rubber sheetings Membranes BR and NR showed a superior resistance to movements. The application of them depends upon their resistance to ozone. Membranes VC–1 and VC–2 may be applied to the roofs where movements of 1 mm are expected. But it is not advisable to bond them to roof deck with strong adhesives.

If any contribution to the study of roofing membranes can be drawn from this paper, it is that these fatigue rupture tests for the membranes with repeated movements were the first trial in our country as far as the author knows and that these tests showed that even small movements may damage the roofing membranes by a number of repetitions.

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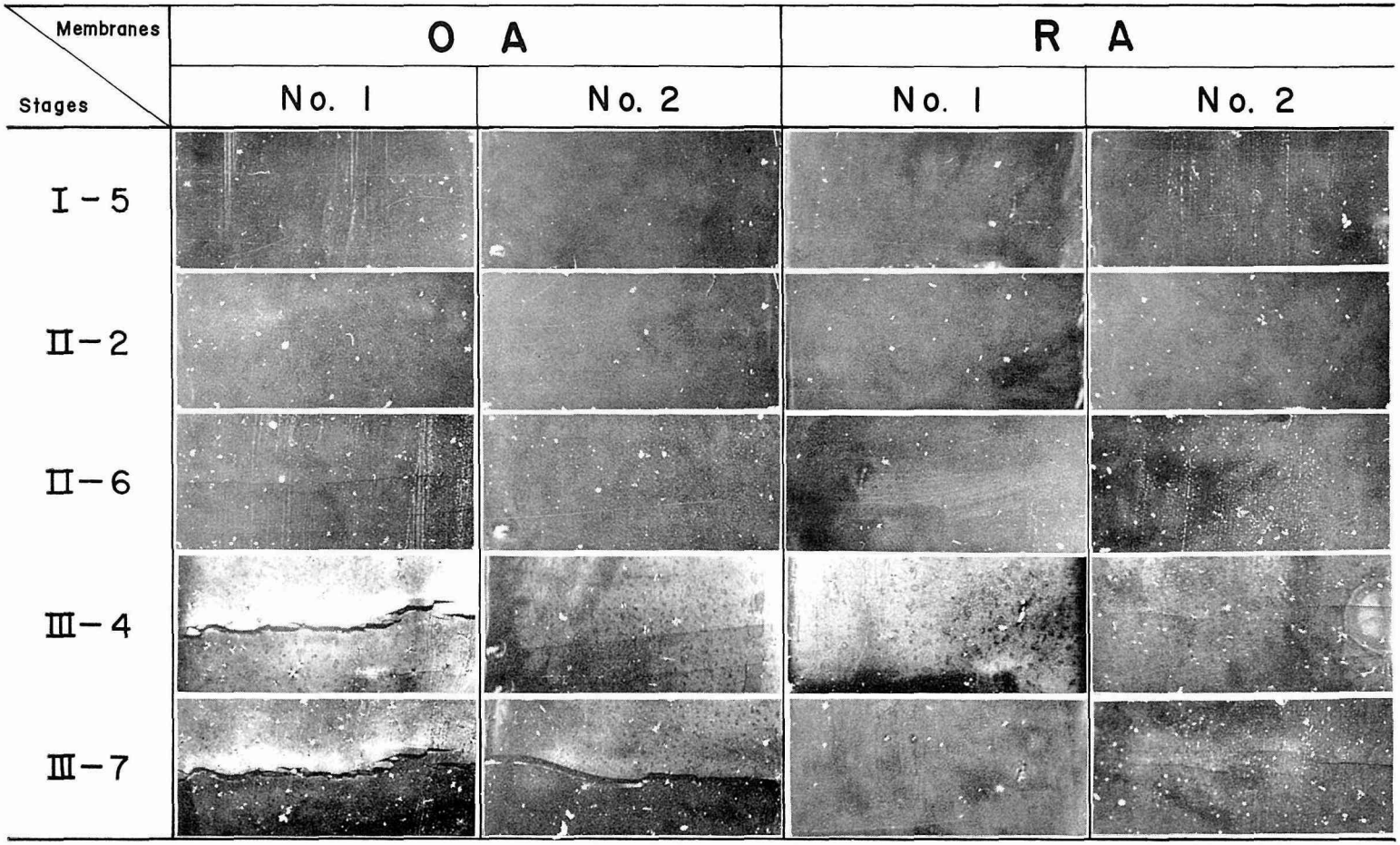

Fig. 7. Test results by Method A (*Part 1*).

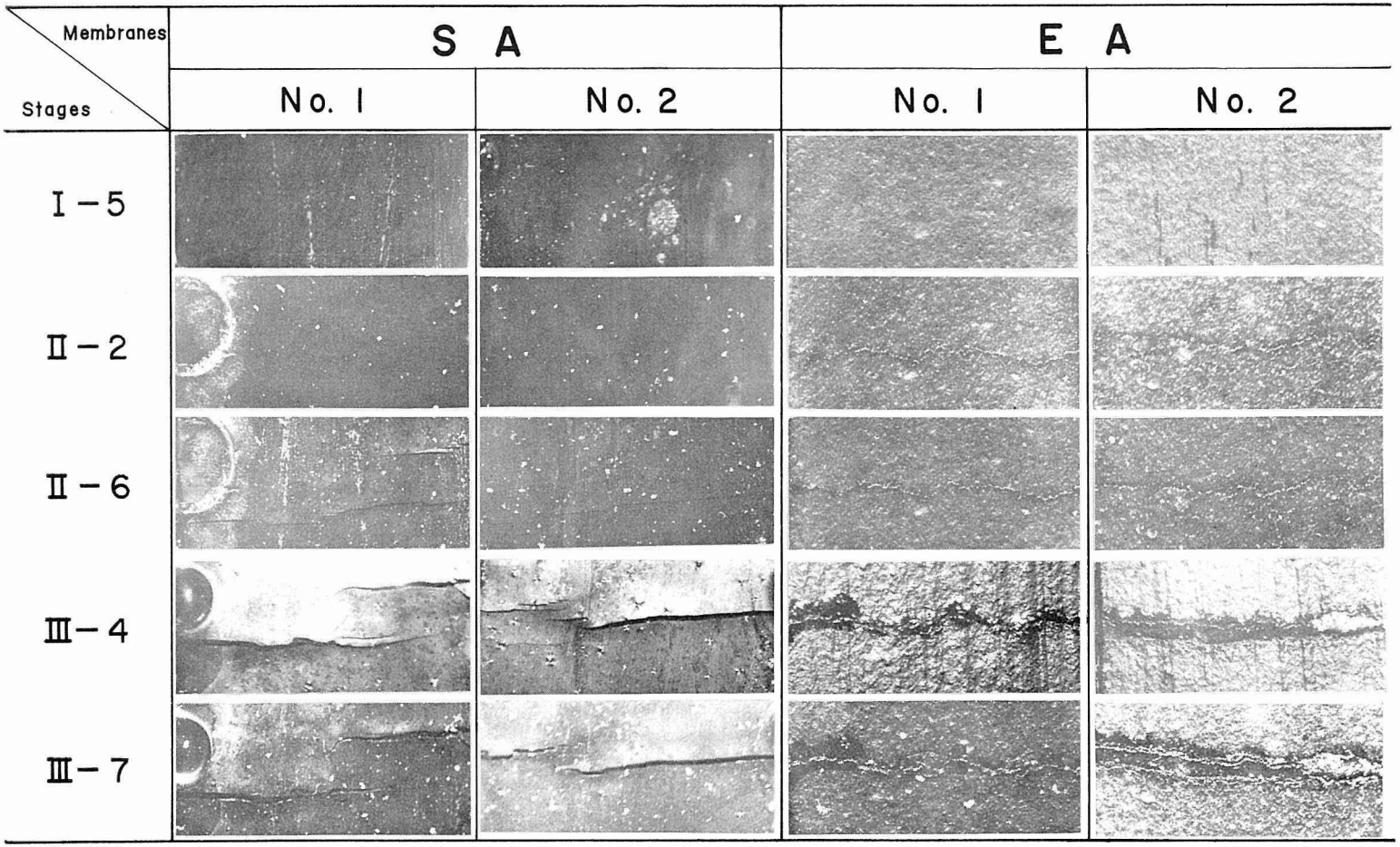

Fig. 8. Test results by Method A (*Part 2*).

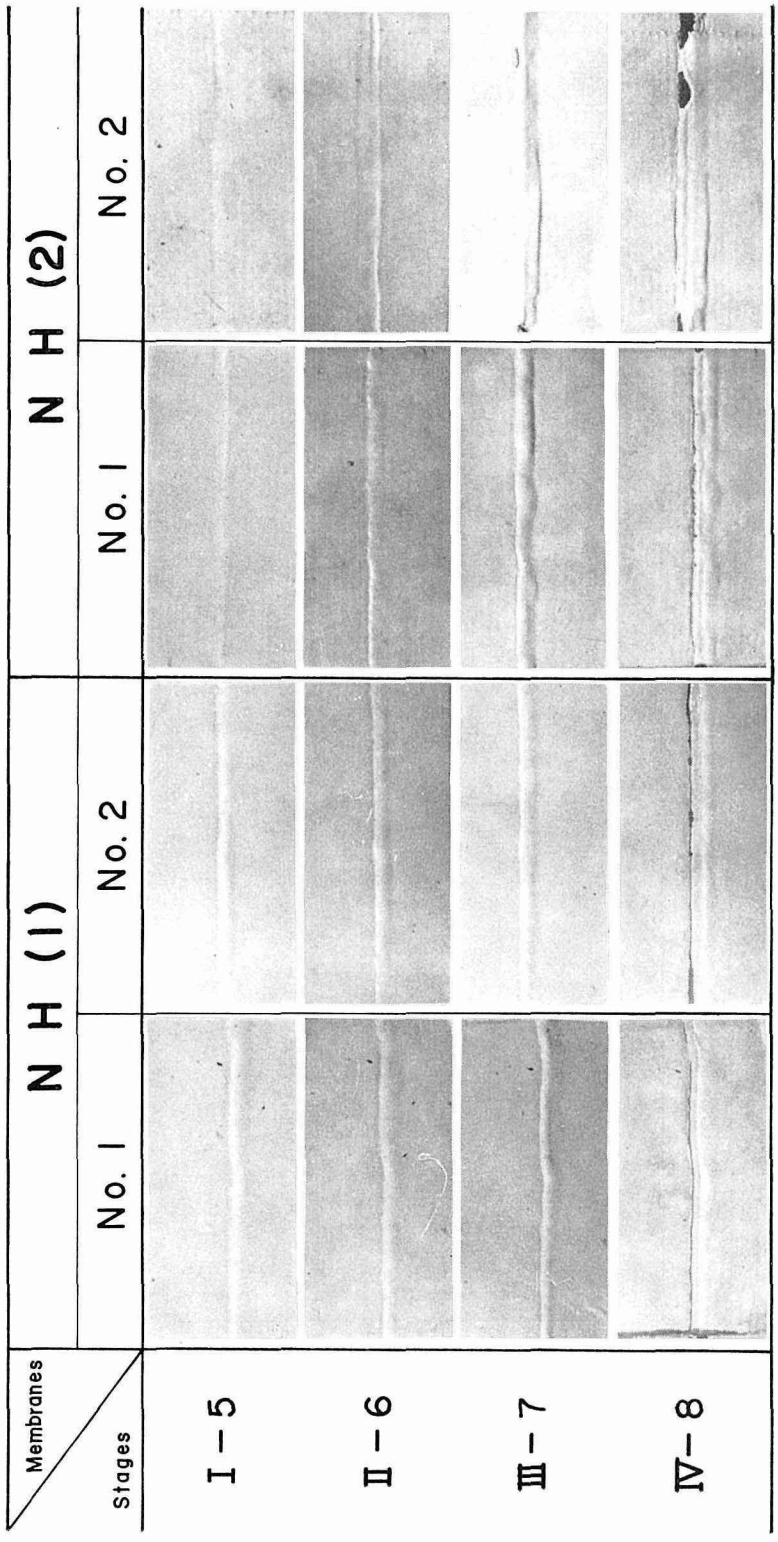

Fig. 9. Test results by Method A (*Part 3*).

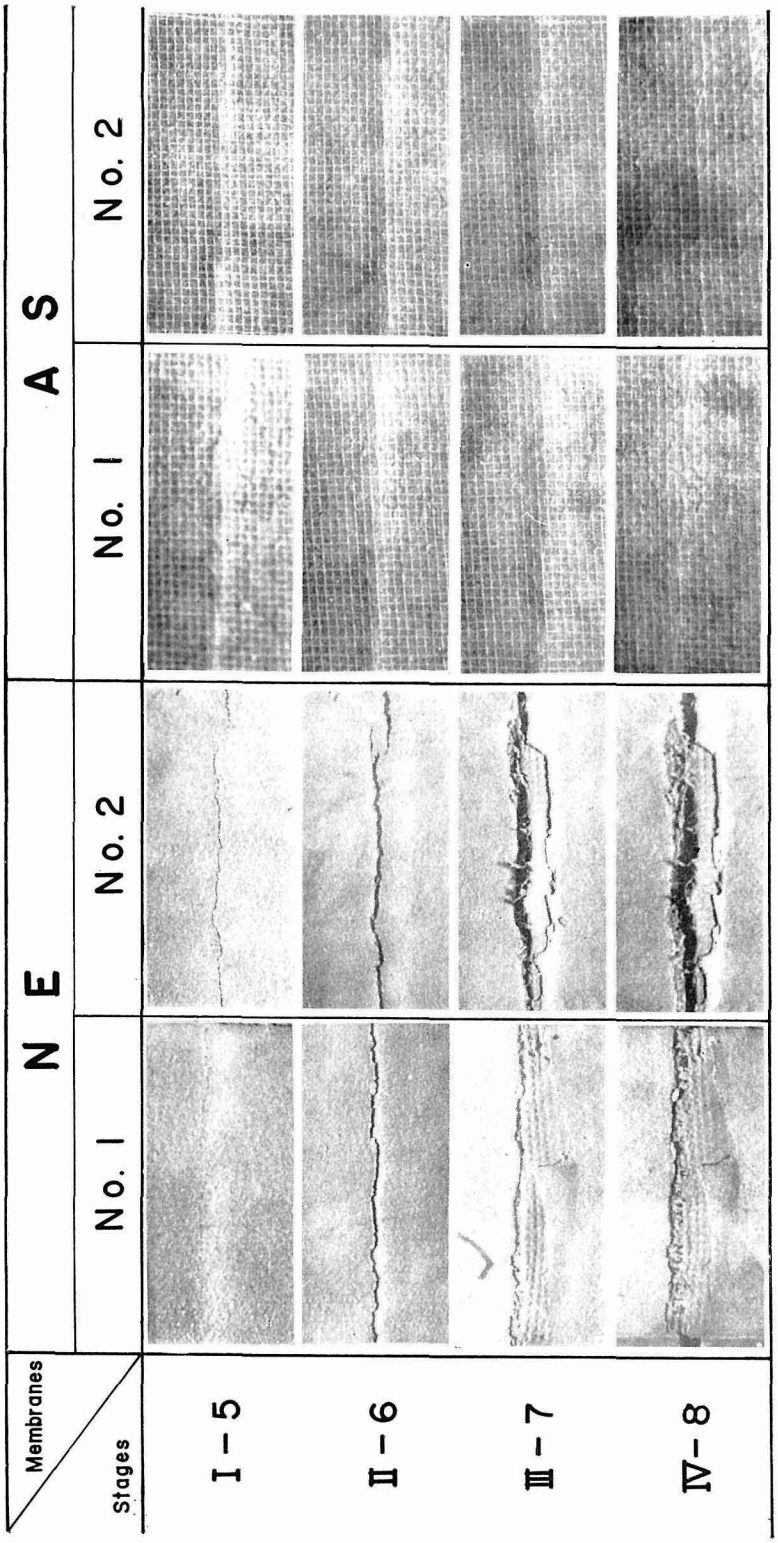

Fig. 10. Test results by Method A (*Part 4*).

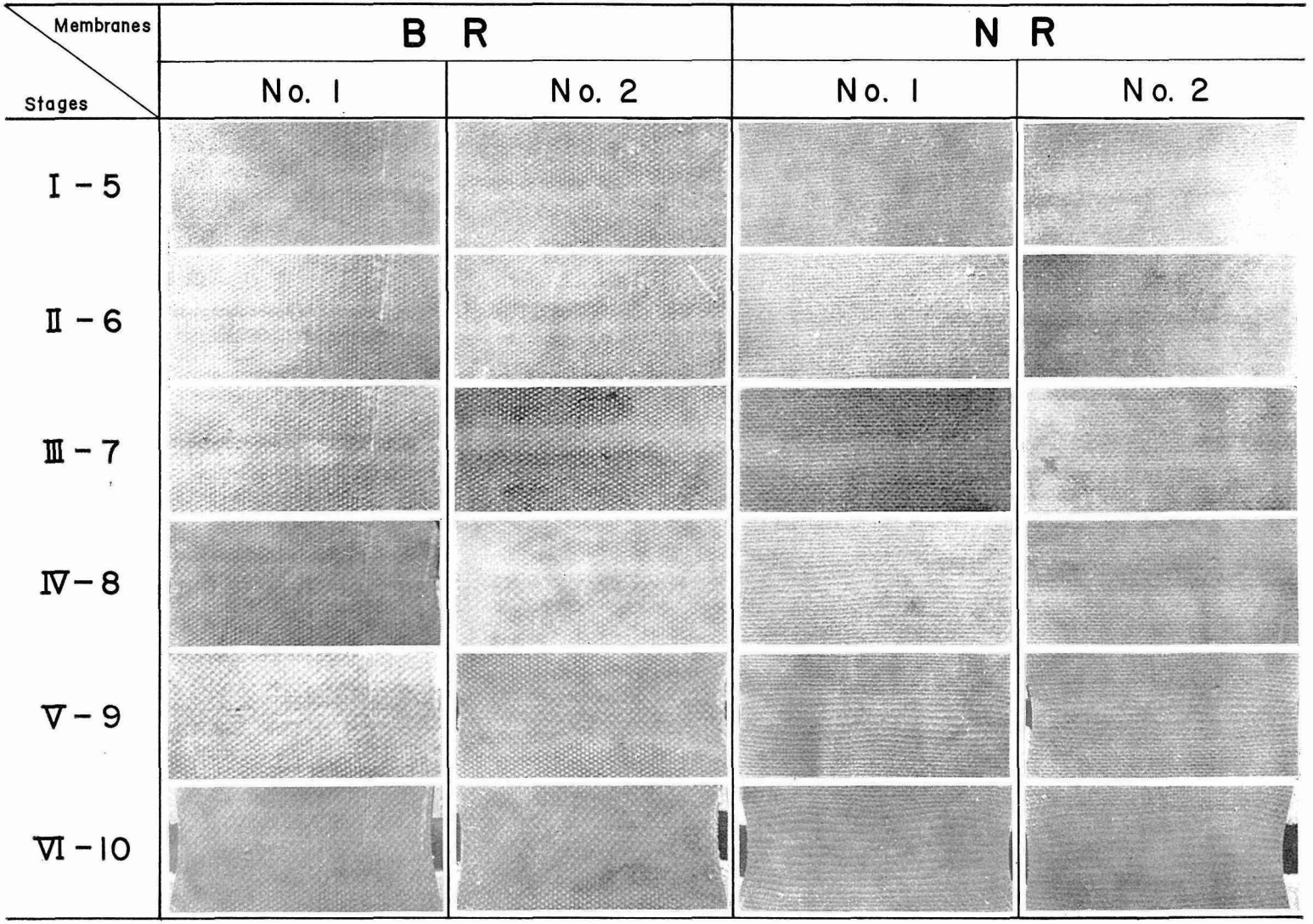

Fig. 11. Test results by Method A (*Part 5*).

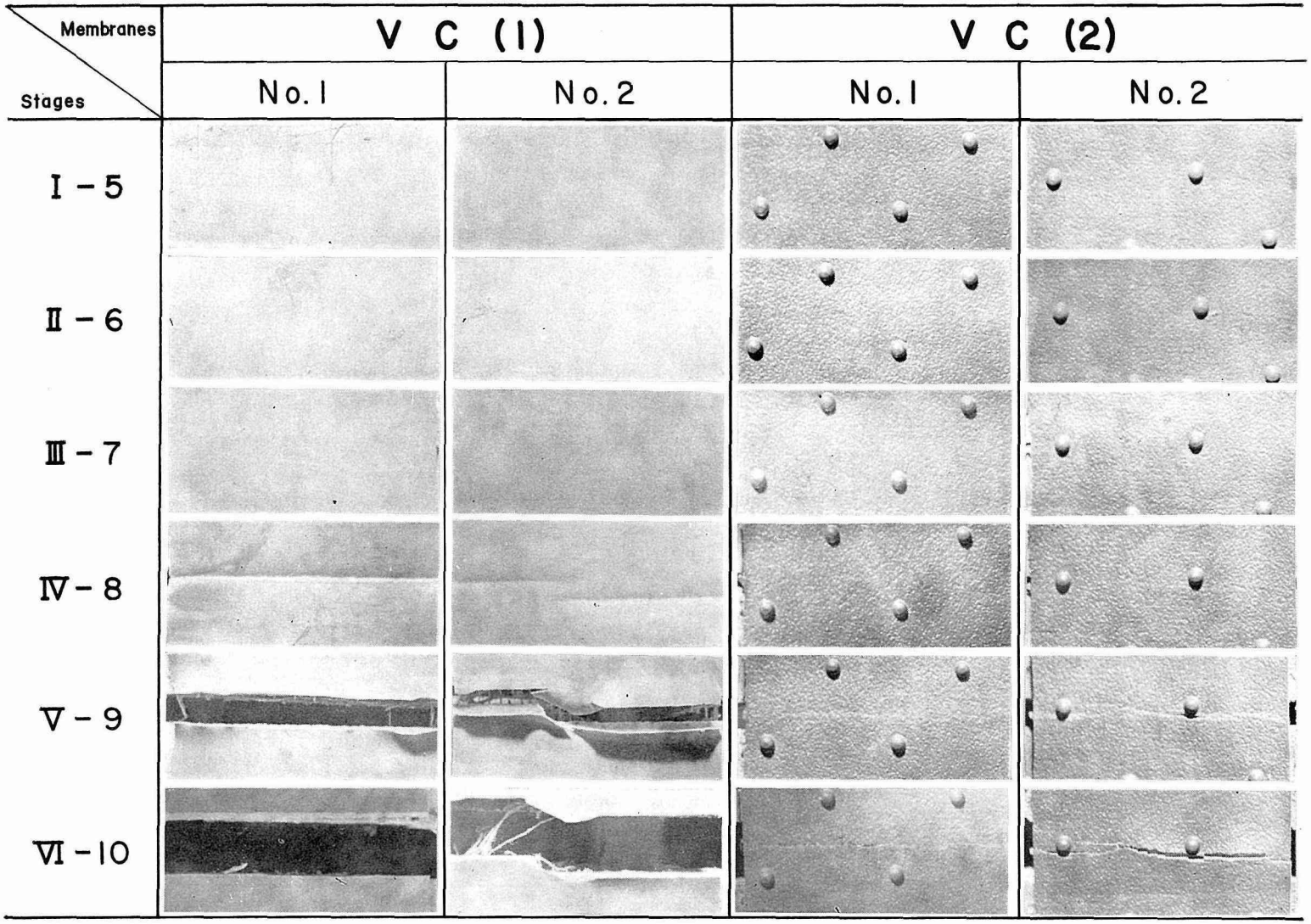

Fig. 12. Test results by Method A (*Part 6*).

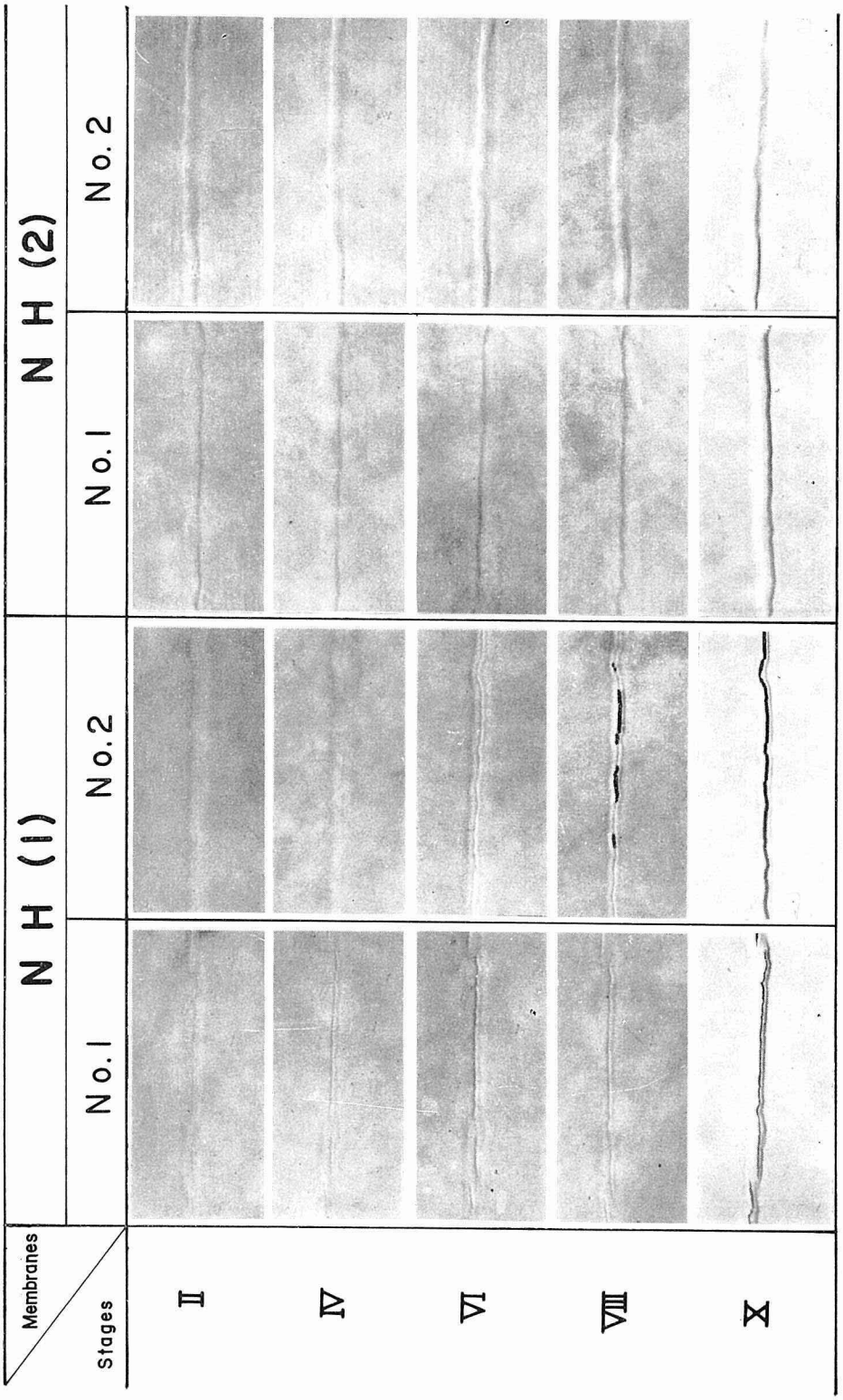

Fig. 13. Test results by Method B (*Part I*).

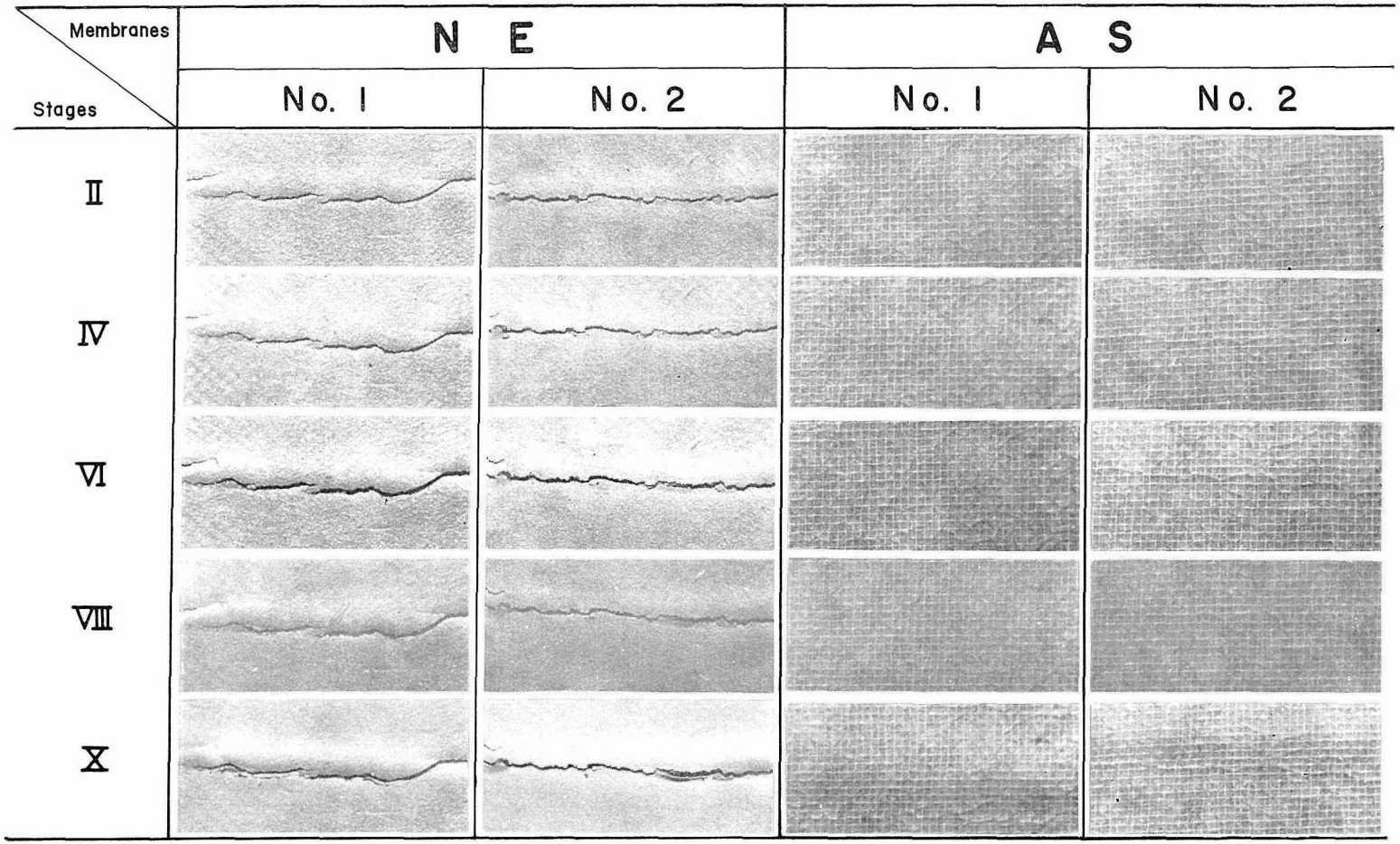

Fig. 14. Test results by Method B (*Part 2*).

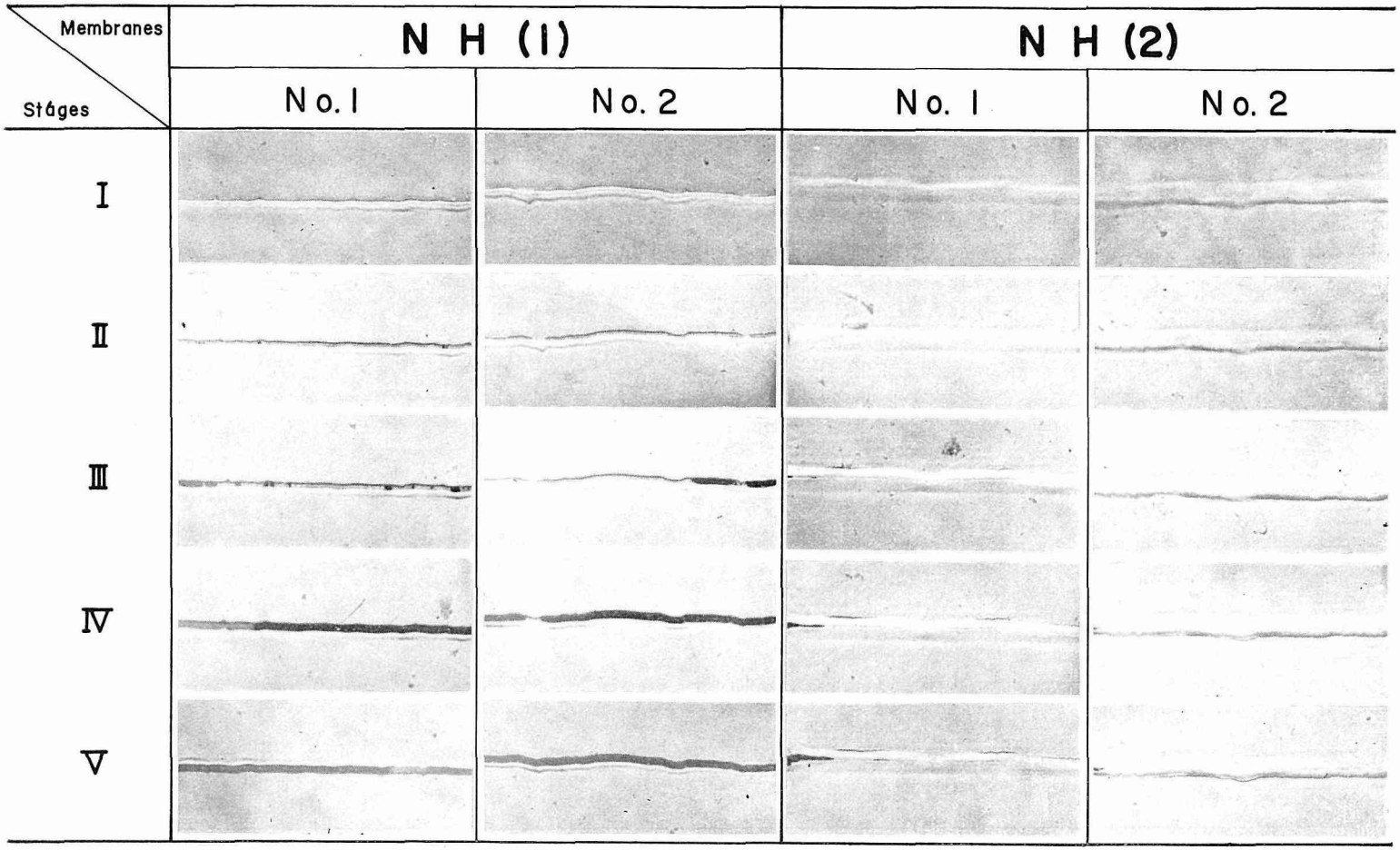

Fig. 15. Test results by Method C (*Part 1*).

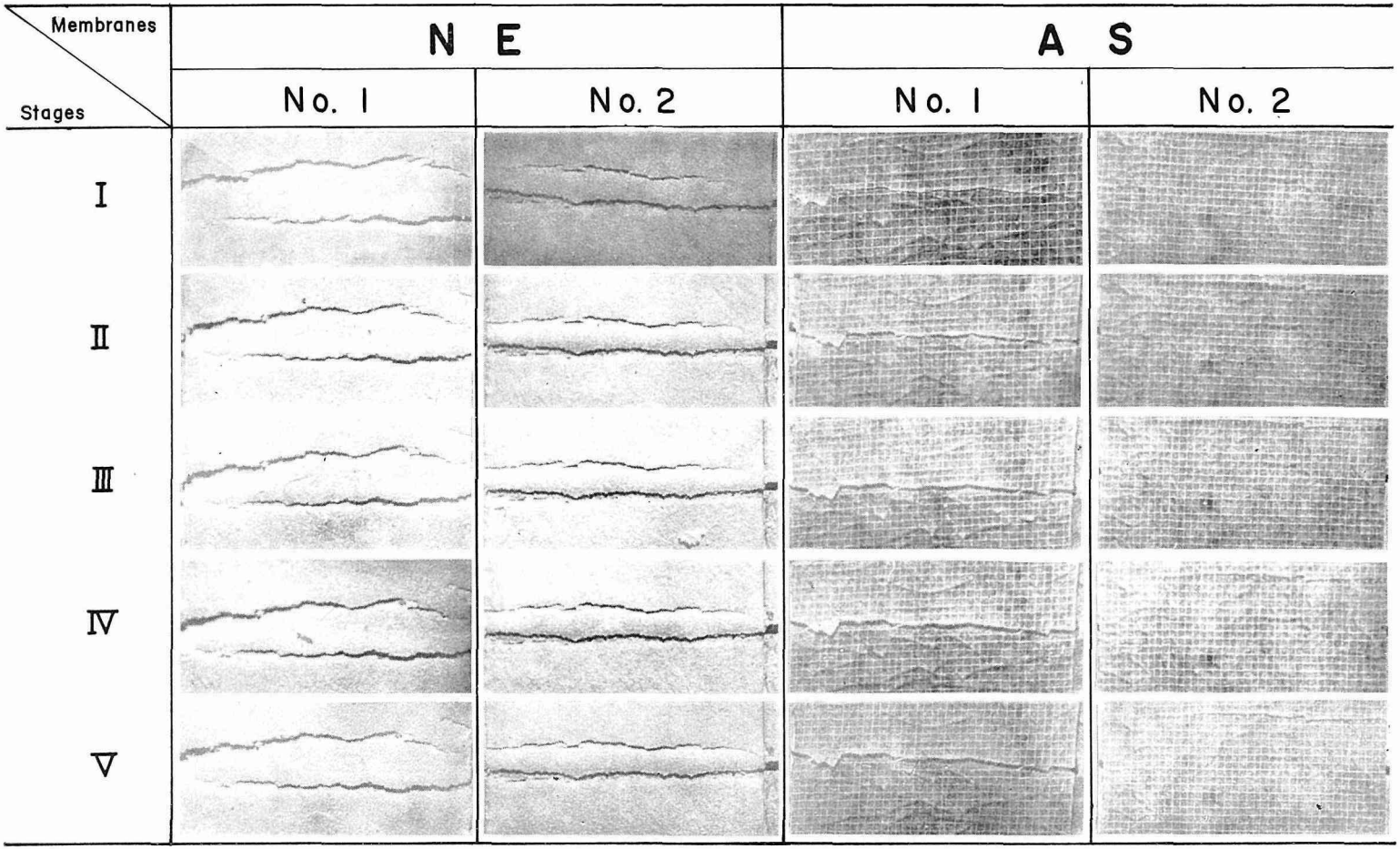

Fig. 16. Test results by Method C (*Part 2*).