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Investigation Program on PWR-Steel-Containment Behavior under Accident Conditions

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Abstract

This report is a first documentation of the KfK/PNS activities and plans to investigate the behaviour of steel containments under accident conditions.

The investigations will deal with a free standing spherical containment shell built for the latest type of a German pressurized water reactor. The diameter of the containment shell is 56 m. The minimum wall thickness is 38 mm. The material used is the ferritic steel 15MnNi63.

According to the actual planning the program is concerned with four different problems which are beyond the common design and licensing practice:

Containment behavior under quasi-static pressure increase up to containment failure.

Containment behavior under high transient pressures.

Containment oscillations due to earthquake loadings; consideration of shell imperfections.

Containment buckling due to earthquake loadings.

The investigation program consists of both theoretical and experimental activities including membrane tests allowing for very high plastic strains and oscillation tests with a thin-walled, high-accurate spherical shell.

Forschungsprogramm für DWR-Sicherheitsbehälter unter Unfall-Belastungen

Die Untersuchungen werden durchgeführt für einen freistehenden kugelförmigen Sicherheitsbehälter, wie er bei neueren deutschen Druckwasserreaktoren üblich ist. Der Durchmesser beträgt 56 m, die Wandstärke im nicht verstärkten Behälterbereich ist 38 mm. Als Werkstoff wird der ferritische Stahl 15MnNi63 verwendet.

Nach den gegenwärtigen Planungen werden vier Problemkreise bearbeitet, die jenseits der üblichen Analysen bei Auslegung und Genehmigung liegen:

Verhalten des Sicherheitsbehälters bei quasi-statischem Innendruck-Anstieg bis zum Versagenspunkt.

Verhalten des Sicherheitsbehälters unter hohen transienten Drücken.

Schwingungen des Sicherheitsbehälters bei Erdbeben-Beanspruchung; Beachtung von Schalen-Imperfektionen.

Beulen des Sicherheitsbehälters bei Erdbeben-Beanspruchung.

Das Programm umfaßt theoretische und experimentelle Untersuchungen. Unter anderem werden Membran-Tests unter sehr hohen plastischen Dehnungen und Schwingungs-Experimente mit einem sehr dünnwandigen, hochgenauen Kugelschalen-Modell durchgeführt.

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1. Containment Behavior under Quasi-static Pressure Increase

1.1 The Problems

During the last years core melt accidents have been discussed rather extensively. It has been found that the pressure inside the containment increases rather slowly. Therefore failure of the containment is expected only after a long delay time of several days and the radioactive consequences to the environment are assessed to be much lower than assumed some years ago. However, in order to confirm these findings a reliable determination of the maximum pressure before containment failure and the type of containment failure is necessary.

For investigation of this problem the weak parts of the containment must be identified. From extensive experiments carried out at the MPA-Stuttgart and from broad experience gained during ultrasonic screening of many containment shells it is known that weldings do not represent the weak parts. Also the different types of containment nozzles, the containment reinforcement plates around the nozzles and the containment clamping at the bottom are designed such that failure should not occur there. This has been shown by several stress analyses. Even the contact between an extremely deformed containment shell and protrusions of the encasing concrete shell are not likely to initiate containment failure. This has been shown by a large deformation shell analysis with the computer program ROTMEM described later.

Finally as rather weak parts of the containment shell the following regions have been identified:

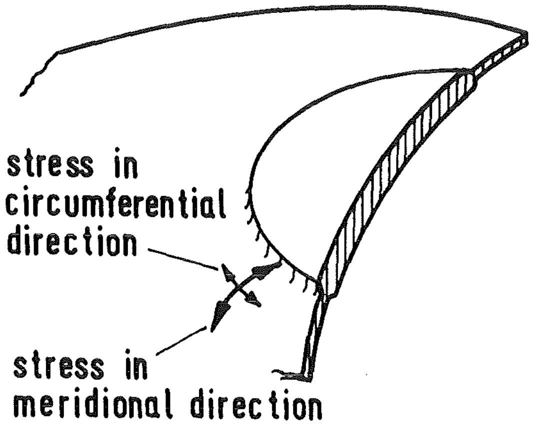

Fig. 1: Stresses in the neighbourhood of reinforced sections

- Zones of the spherical shell in the neighbourhood of reinforced sections. Usually these sections contain nozzles, locks, etc. Since the strains in the reinforced sections are rather low, the circumferential strains and stresses around the reinforced sections must be low, too. In order to satisfy equilibrium with the internal pressure, the stresses in the meridional direction must be rather high (Fig. 1). That means large plastic strains may be concentrated in the neighbourhood of reinforced sections.

- The bolted connection between the spherical shell and the material lock. Here a large number of small holes are drilled in the shell without any reinforcement (Fig. 2). That means, considerable local plastic strains may be concentrated around these holes.

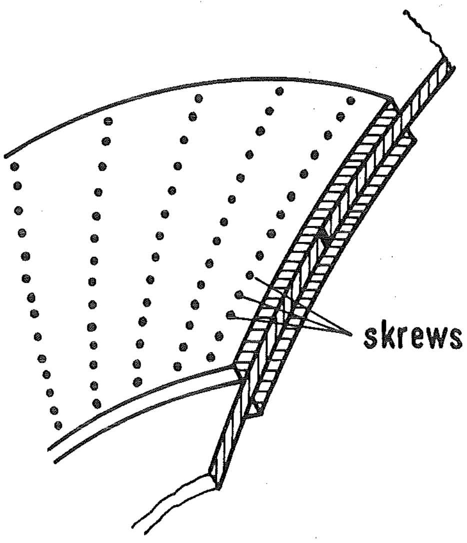

Fig. 2: Bolted connection between spherical shell and material lock

Both problems will be investigated in some detail in order to determine both, the maximum pressure before failure and the type of failure.

1.2 Theoretical Investigations

As computational tool the program ROTMEM has been developed. It allows for calculation of the membranestresses and strains of an axisymmetric shell under axisymmetric pressure loading. Any elastic-plastic material behavior (in the present version without unloading) can be considered. The two-axial state of stresses is treated according to the theory of Hencky (nonlinear relations between stresses and strains) or according to Prandtl-Reuss (nonlinear relations between stress increments and strain increments). Large deformations are considered, i.e. the equilibrium conditions are satisfied at the deformed shell.

The program ROTMEM will be used to investigate the strains in those zones of the spherical shell which are in the neighbourhood of reinforced circular sections. The axes of the circular sections are used as axes of symmetry. That means, mutual interaction between different nozzles are not considered. This is allowed, since the stress peturbations due to the reinforced sections have a rather local character. As indicated above, also bending stresses are not considered. This is acceptable, since the expected bending of the thin containment shell will not cause high plastic strains.

Due to these simplifications and neglects of unessential effects high computational effort may be spent to important effects. For instance, ROTMEM allows for high spatial resolutions around the reinforced sections (Fig. 3). Furthermore it allows for many load steps which are necessary for ferritic steel with a sharp elastic-plastic transition region.

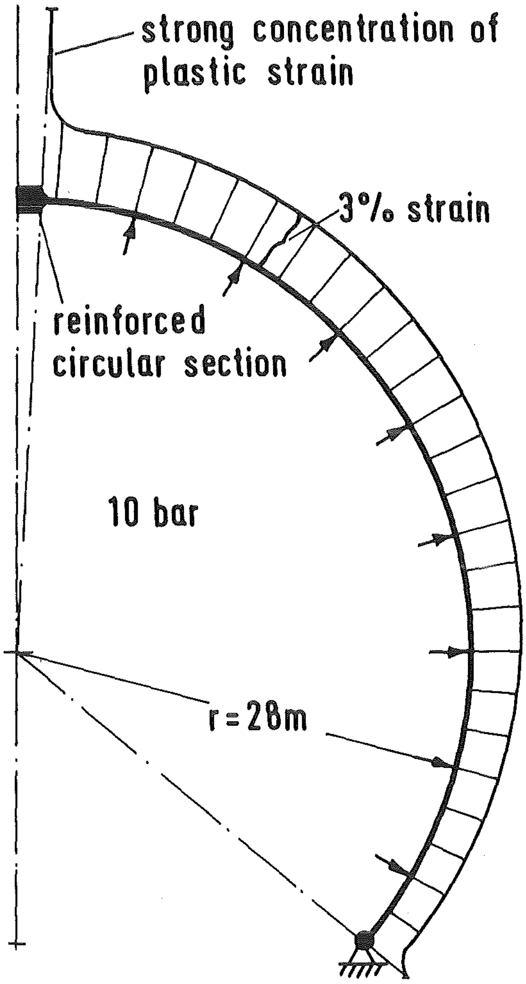

Fig. 3: Preliminary results of the program ROTMEM.
Strong concentrations of plastic strains close to the reinforced circular section require high spatial resolution in this region

1.3 Experimental Investigations

Tests on containment models with excessive internal pressures have been found to be unsuitable, since manufacture of several models in correct scale (thin spherical shells) would be very expensive and miniatur weldings with the same quality as the real containment welding would even be impossible.

Instead tests with plane circular membranes under excessive unilateral pressure - so-called bulge tests - will be done. The plates used to manufacture the membranes are the same as those used for PWR-containments (15MnNi63-sheets with a thickness of 38 mm). The manufacture process for the membranes (facing the plates with a lathe) is relatively simple and the material properties obtained in this way should be realistic. One goal of these tests is to find reliable equations of state (relations between stresses and strains) for the containment material under two-axial stress conditions. Another goal is to get information about the type of failure, e.g. occurrence of leakages, development of necking, propagation of cracks. The third goal is to check the computer program ROTMEM.

The diameter of the membrans used is 800 mm, the thickness is 2 mm with a tolerance of ±0.04 mm. Some membranes will be smooth, others will contain reinforced sections with a circular or a rectangular shape and one membrane will probably be provided with a mock-up of the bolted connection between the spherical shell and the material lock. The unilateral pressure will be applied by an oil-hydraulic system. Exceptionally also an air pressure system may be used.[1] During the test the pressure will be increased in steps of about 5 bar until failure. After each step the displacements of a large number of control points marked on the membrane will be measured using a three-coordinate measuring machine (Fig. 4). For the same points also the decreasing thickness of the membrane will be determined using an ultrasonic sensor.

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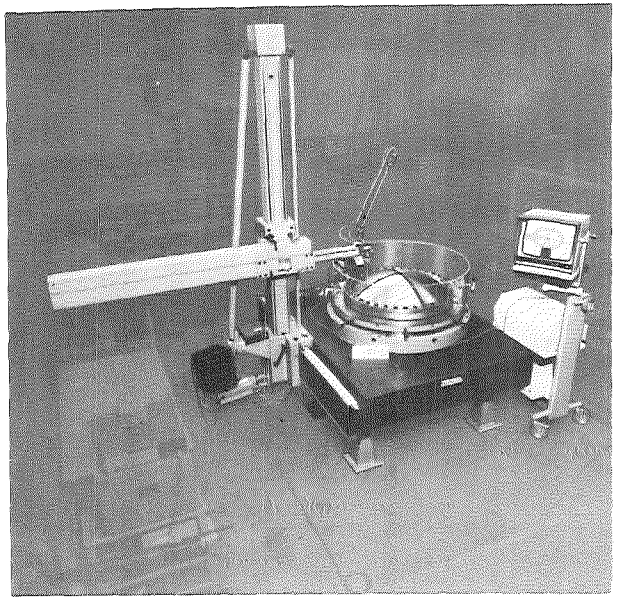
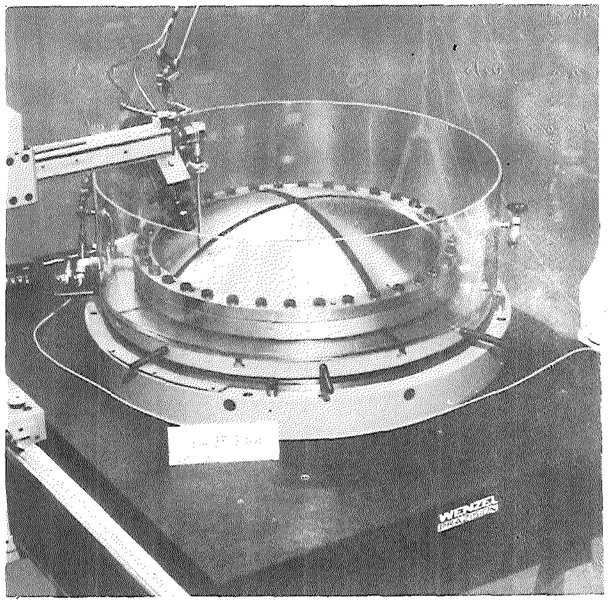
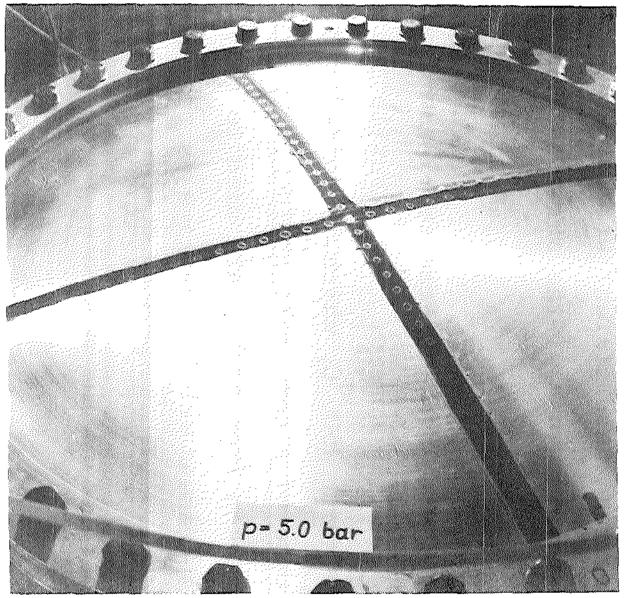
[1] For safety reasons, these tests must be done outdoors and detailed deformation measurements are not possible.



Measuring machine.



Feeler and control points magnified by a television set.



Circular membrane with control points.

Fig. 4: Circular membrane under unilateral pressure.
Investigation by a three-coordinate measuring machine

Based on these data and the pressures the different strain and stress components can be calculated and several points of the stress-strain relation under two-axial conditions can be determined.

These results can then be compared with results from small one-axial tensile tests which will also be carried out. In some of these tensile tests the temperature will be increased to about 150 °C, which is considered to be the containment temperature in case of a core melt accident. Specimens for the small tensile tests will be taken from each plate used to manufacture a membrane. The diameter of the specimens will be the same as the thickness of the membrane and the position of specimens within the thickness of the plate will be the same as the position of the membrane.

Furthermore the results from the small tensile tests can be compared with results from large one-axial tensile tests, where the thickness of the specimens covers the whole cross section of the plates used for PWR containments (Fig. 5). In this way it can be checked, whether the material properties of the membranes are representative for the material properties of PWR containments.

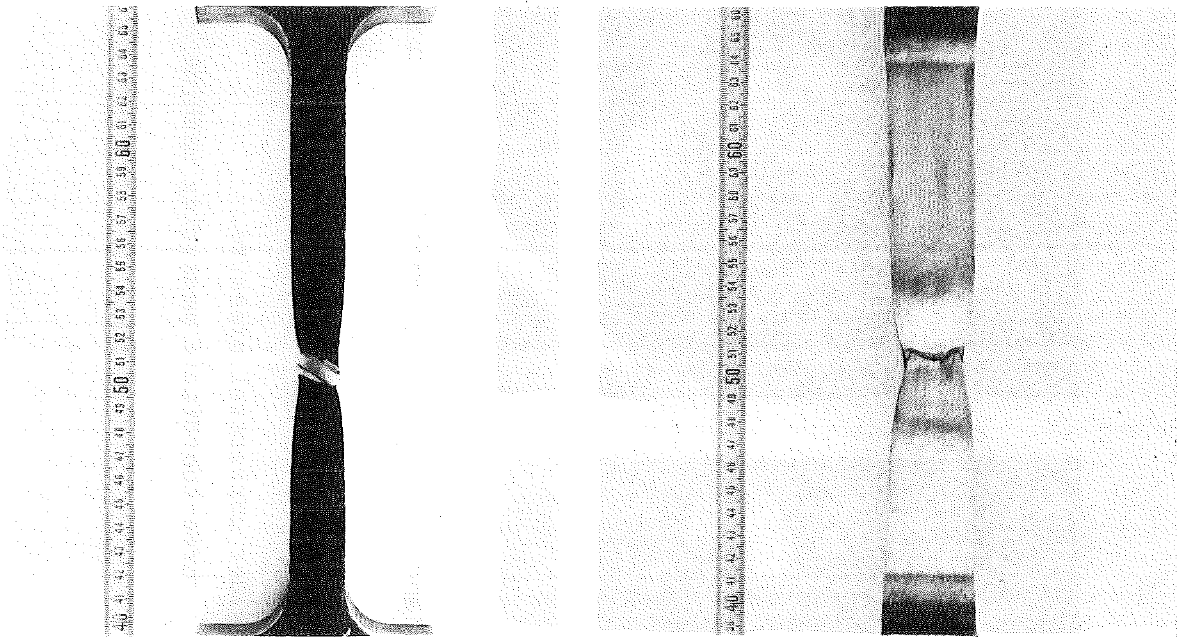


Fig. 5: Large one-axial tensile test

The information about the type of failure obtained from the membrane test will be completed by some slice tests. One slice will be without any hole. Each of the other slices will contain one hole, but the diameters of the holes will be different. Then uniaxial tension stresses will be applied and both the maximum tension stresses and the local deformation before failure will be determined. It is expected that necking occurs before failure and that the maximum tension stresses do not depend very much on the diameter of the hole.

Additional information about the type of failure will be obtained from crack tests. It is expected that the measured stress intensity factors will confirm the occurrence of large plastic deformations before crack propagation.

2. Containment Behavior under High Transient Pressures

In recent years also transient containment loadings caused by postulated hydrogen explosions received increased attention. Here it should be shown that even strong transient pressures are not able to damage the containment such that it looses its tightness. However, certain plastic deformations should be tolerable.

The investigation of this problem is closely related to the containment under quasi-static pressure increase discussed before. Especially the weak parts of the containment are the same.

However, it should be noted that now the containment loading may have a non-uniform character and that the containment stiffness may be relatively low in this case.

As computational tool an extended version of the program ROTMEM will be used where inertia terms are added.

Special experimental investigations are not planned so far. However, it is believed that many of the results obtained for the quasi-static problem are applicable here. Furthermore, also some of the oscillation experiments described in the next paragraph will give a certain support, as long as the containment deformations do not exceed the elastic region.

3. Containment Oscillations due to Earthquake Loadings

3.1 The Problem

Analysis of containments under different types of dynamic loadings is common licencing practice. The computations are based on simplified models. Deviations from the ideal spherical geometry caused by a number of different nozzles with reinforced sections or due to inevitable manufactoring tolerances are usually not considered.

However, from several experiments with thin cylindrical shells it is known that small deviations from the ideal geometry may have significant influence on the dynamic response. For instance a cylindrical shell under earthquake excitation should oscillate only in modes with first circumferential order. In reality, inevitable small imperfections give rise to oscillations in modes with higher circumferential order. Since the stiffness of thin shells against such modes is rather low, the amplitudes of such modes can reach rather large values. The strong influence of imperfections has also been studied by theoretical methods (Fig. 6).

It is conceivable that this effect can also occur in thin spherical shells. However, no corresponding investigations are known so far. Therefore investigations to this problem will be carried out within this program.

3.2 Theoretical Investigations

Computational methods must still be developed. It is believed that modelling of the slightly imperfect geometry by standard methods will not be appropriate, since the geometric deviation might be in the order of computational inaccuracies. Rather special methods where the influence of imperfections is studied directly (perturbation methods) should be applied.

3.3 Experimental Investigations

It is evident that the theoretical investigations mentioned before should be checked and completed by experimental work. However, manufactoring of an appropriate spherical shell model is very difficult. The large dimensions and the high manufacturing standard of real containments lead to very small relative tolerances. But the model should reveal even smaller tolerances in order to provide first the reference results for an almost ideal geometry.

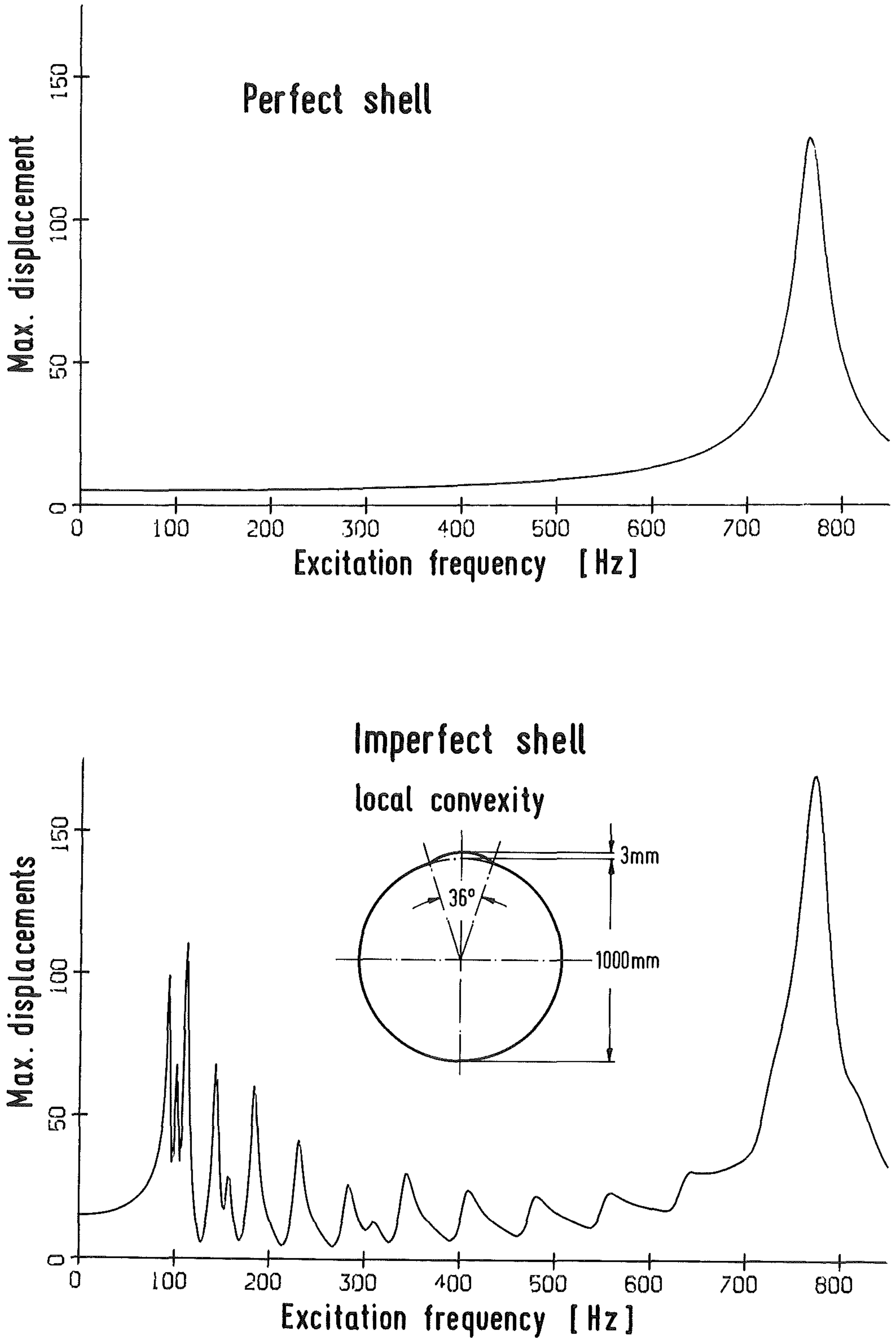


Fig. 6: Cylindrical shell, 1000 mm diameter, 1600 mm hight, 3 mm wall thickness without and with imperfection under harmonic base excitation. For excitation frequencies lower than 600 Hz the maximum displacements of the imperfect shell are considerably higher than for the perfect shell.

Later then results should be obtained for geometries with well defined disturbances, i.e. for geometries with additional masses or stiffening plates attached to the shell.

Careful consideration showed that usual manufactoring processes for the model like deep drawing or welding are by far not sufficient to satisfy the above requirements. Finally it turned out that manufacturing the model by turning using a numerical controlled lathe will probably provide the best results. Details of the manufactoring process are mentioned in Fig. 7 and 8.

According to the largest lathe available, the diameter of the spherical shell model has been determined to about 1400 mm. The wall thickness will be 1 mm. The angular aperture will be 100°. While the accuracy of the shape is expected to become relatively high with deviations less then 1 ‰ of the sphere diameter, the accuracy of the wall thickness will be relatively small with deviations in the order of 10 % of the thickness. However, the later deviations are expected to have a smooth distribution which can be analytically described, if required. The accuracy of the shape will be determined by a measuring machine. The accuracy of the thickness will be determined using an ultrasonic sensor.

To obtain the eigenfrequencies and the corresponding mode shapes, an experimental modal analysis of the spherical shell model will be carried out. Both undisturbed models (original) and disturbed models (with additional masses and stiffening plates) will be examined. The spherical shell models will be subjected to transient excitation with an impuls hammer, a snapback-device or a narrow-band random force of short duration. The corresponding response will be simultaneously measured with a set of miniature accelerometers or contactless displacement transducers. To extract the set of eigenfrequencies, mode shapes and critical damping ratios from the simultaneously measured response signals, a modified version of the computer code EVA will be used. It had been developed and applied to other shell and structural dynamics problems in recent years. The objective of the intended modification is the improvement of the frequency resolution and of the ability to separate multiple modes. This is expected to be necessary because of the extraordinarilly dense spectrum of eigenfrequencies of spherical shells obtained in precalculations. The experimental procedure will be tested during preliminary modal measurements performed with a welded forerunner model of the shell having a diameter of only 700 mm (Figs. 9a and b).

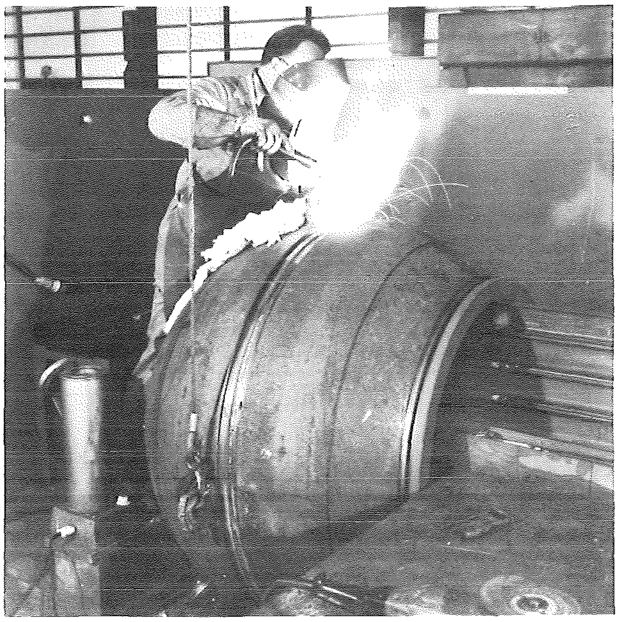
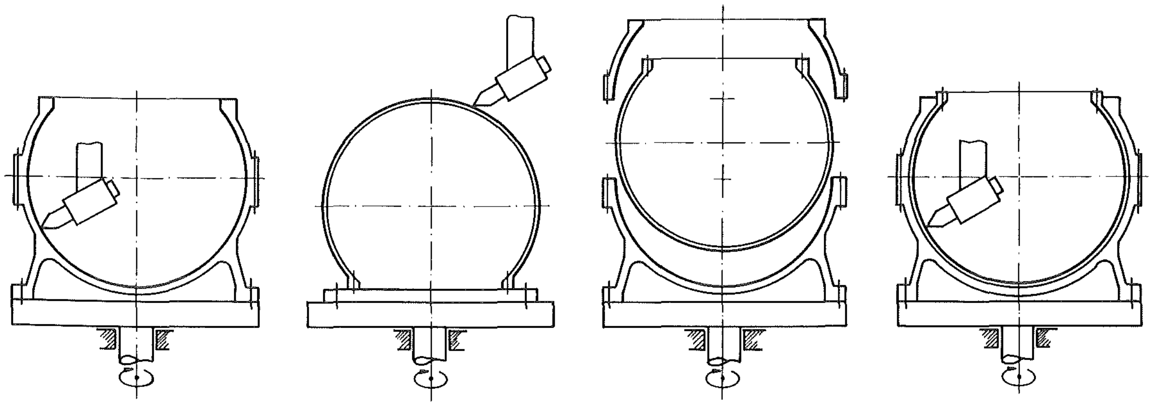


Fig. 7: Welding of the unfashioned sphere; wall thickness about 30 mm



1. Inside cutting of supporting case
2. Outside cutting of the sphere
3. Clamping of sphere within the case
4. Inside cutting of the sphere

Fig. 8: Cutting of the sphere using a numerically controlled lathe

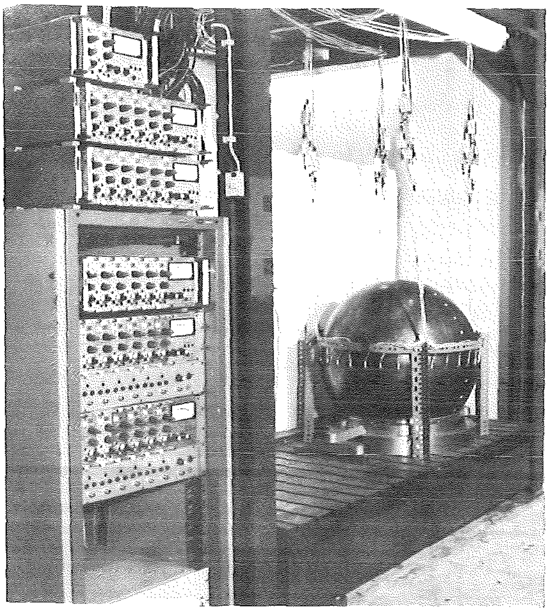


Fig. 9a: Experimental setup for modal measurements

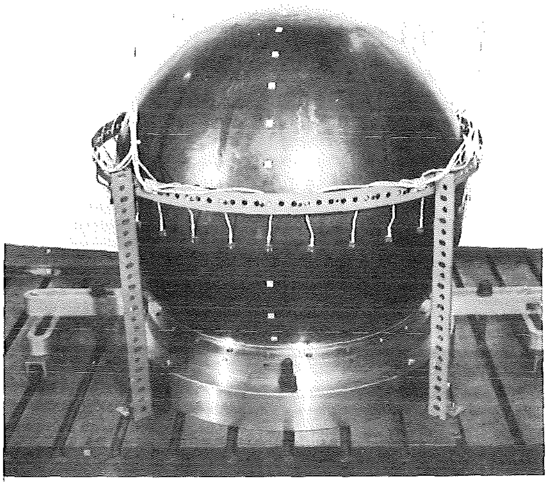


Fig. 9b: Spherical test model with installed accelerometers

In the later stage of experiments, the spherical model will be mounted on a table coupled with an eletrodynamic shaker and subjected to harmonic or random excitation. Both the excitation and the response will be measured and mutually correlated. Special attention will be paid to the excitability of modes with higher circumferential orders and to the influence caused by shell imperfections. These experiments are planed to support the theoretical work on the earthquake loadings of containments.

4. Containment Buckling

The lowest oscillation mode of the containment under earthquake loading is similar to the lowest oscillation mode of a short beam (Fig. 10). During half the oscillation period the meridional membrane stresses in the lower part of the containment shell assume negative values. As a consequence, during this time, local buckling might occur. This effect should be investigated in more detail.

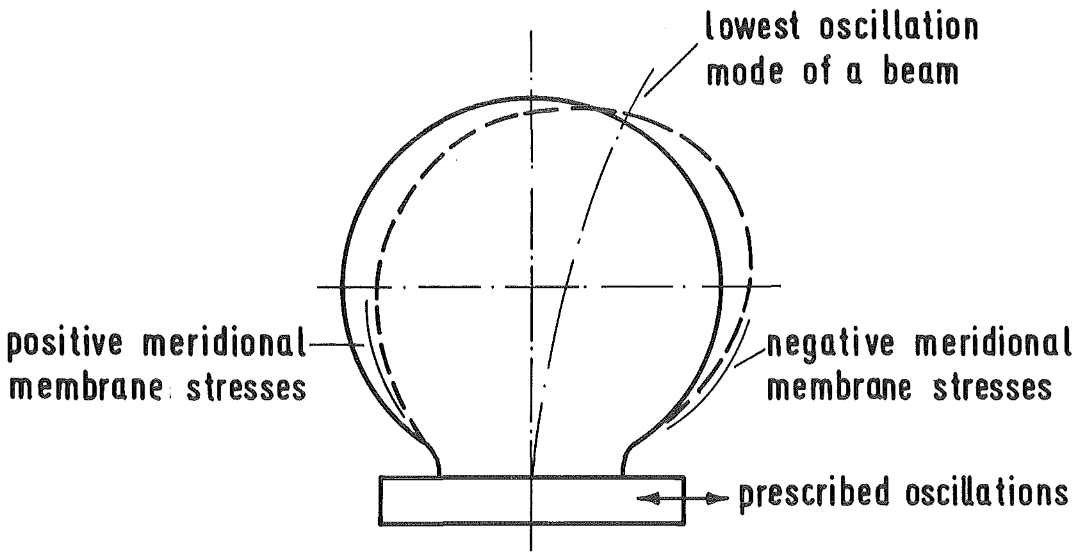


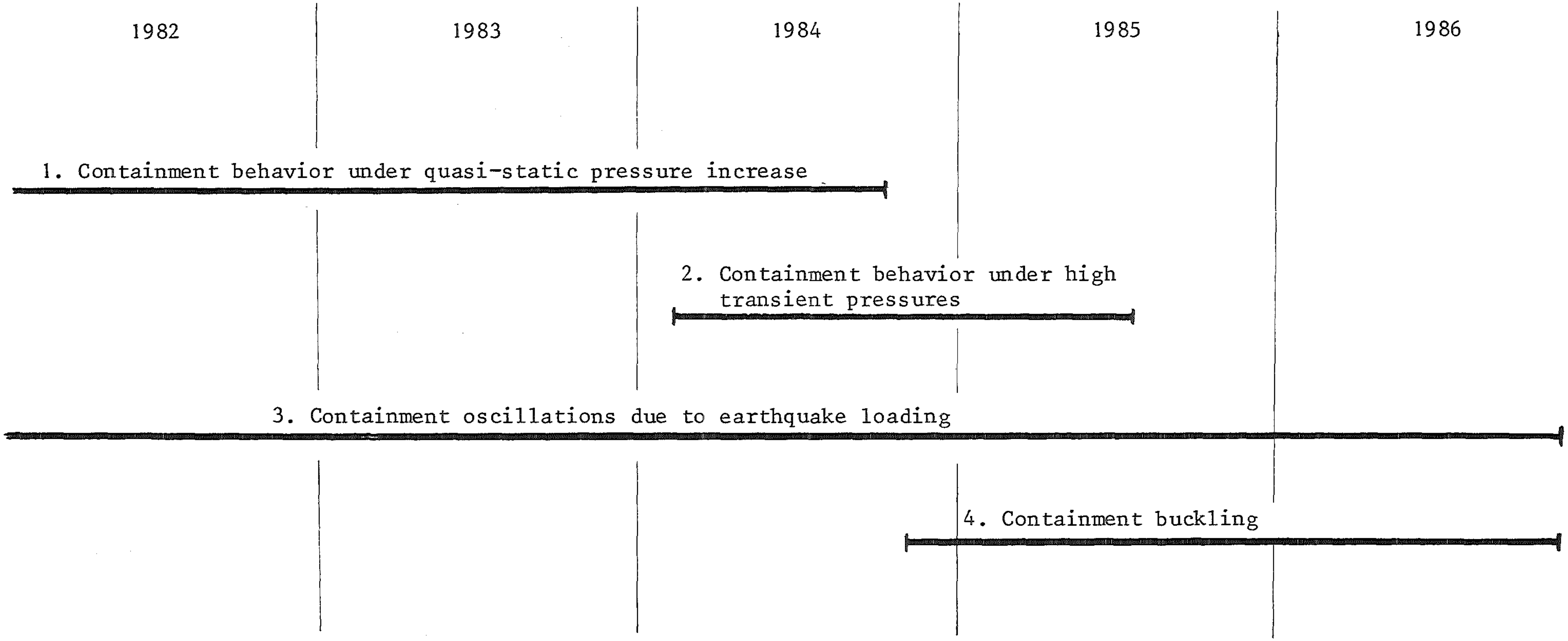
Fig. 10: Lowest oscillation mode and resulting membrane stresses of the containment shell

The computations may possibly be based on known methods where large deformations are considered.

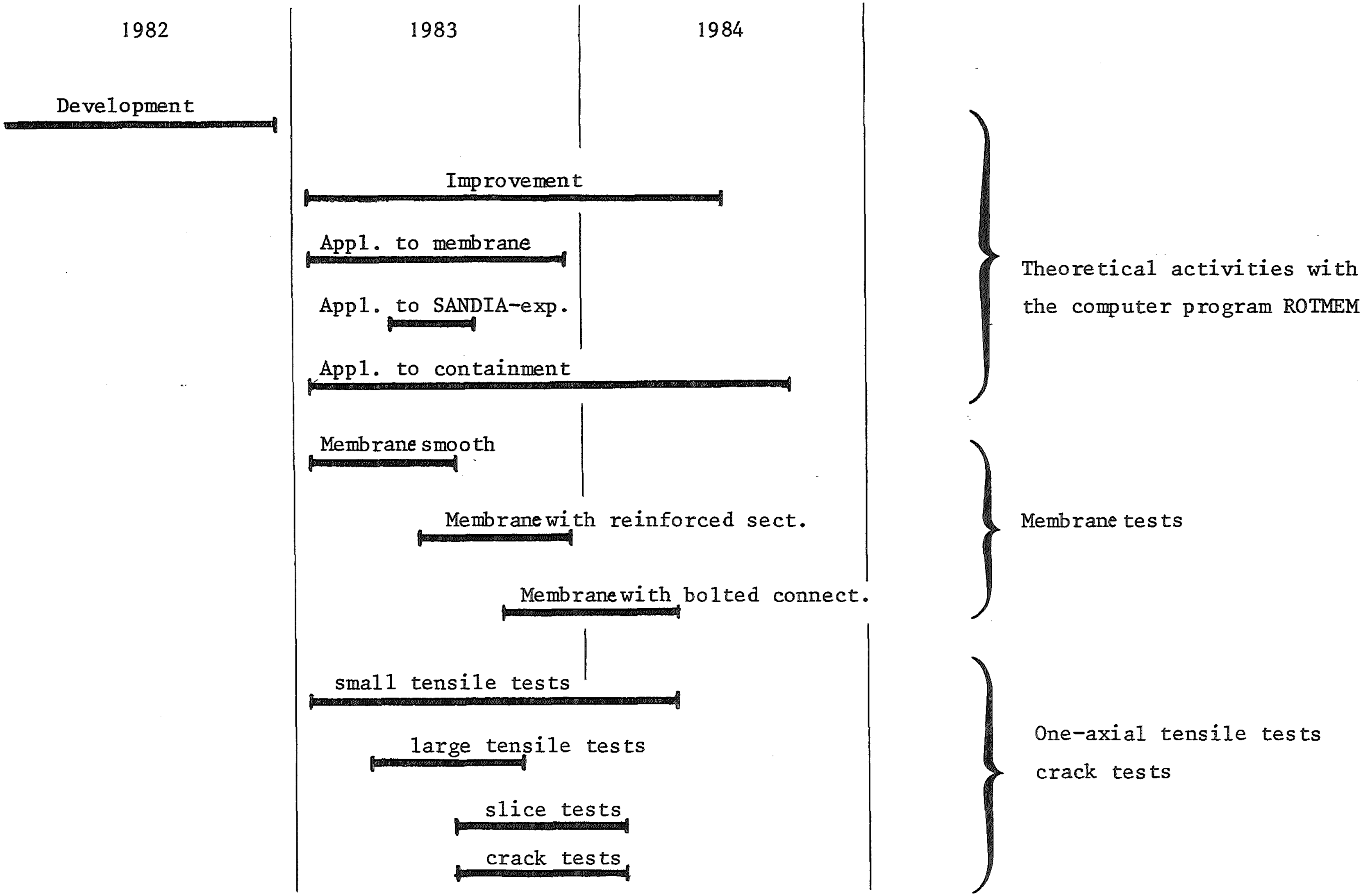
More important are appropriate experiments. They will be done using the high accurate spherical shell manufactured for the oscillation experiments described in the paragraph before. In a first series of tests the earthquake loading will be approximated by a horizontal static force applied at the upper pole of the spherical shell. This force will be monotonically increased close to the point of buckling. However, care must be taken since during these tests buckling should not damage the model. Especially plastic deformations should not occur.

5. Time Schedule

Time schedule - General view -



Time schedule - Containment behavior under quasi-static pressure increase -



Time schedule - Containment oscillations due to earthquake loading -