ANALYSIS OF LMFBR EXPLOSION MODEL EXPERIMENTS BY MEANS OF THE SURBOUM-II CODE

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SUMMARY

During the last four years experiments were carried out at JRC-Ispra in the frame of a collaboration contract between BELGONUCLÉAIRE and EURATOM to simulate in small scale vessels the occurrence of an Hypothetical Core Disruptive Accident (h c d a) for the SNR-300 reactor.

Some of the experimental results collected in the course of this programme were already discussed elsewhere.

In parallel with the experimental programme, the 2D computer code SURBOUM-II has been developed since 1968 by BELGONUCLÉAIRE, and since late 1972 till late 1974 in collaboration with the UKAEA. That code computes the two-dimensional fluid flow within the system in case of a core explosion. The fluid is assumed uncompressible and the deformations of the concentric shell(s) and vessel(s) are calculated by means of the thin shell theory. Perforated dip plates which are included in the model are treated as a particular type of boundary conditions involving empirical pressure drop versus flow relationships.

The first part of the interpretation work was the determination of the pressure-volume relationship of the slow burning charge used to simulate the h c d a. This has been achieved by an original trial and error method built in the code which fits best the experimental impulse time records obtained in bare charge experiments fired in overstrong vessels.

Other experiments carried out in overstrong vessels and involving perforated dip plate above the core to damp out the fluid impact on the roof were calculated and the comparison of the theoretical and experimental impulse time curves was satisfactory.

Further experiments, including or not the perforated dip plate, carried out in yielding vessels were also interpreted. For those experiments the scope of the work was the comparison of calculated and measured deformation of the vessel.

The agreement obtained is satisfactory, though the code seems to overestimate slightly the final deformation. This demonstrates the ability of the SURBOUM-II code to predict safely the phenomena involved in the Hypothetical Core Disruptive Accident.

1. Introduction

Since 1970 the BELGONUCLEAIRE company has undertaken in cooperation with the Euratom Joint Research Center at ISPRA the simulation of LMFBR Hypothetical Core Disruptive Accident (h c d a) by means of the deflagration of a suitable pyrotechnic mixture in small scale vessels. After several series of 1/13 scaled down experiments were carried out, a final shot at larger scale (1/6), intended to represent the SNR-300 h c d a, will be done in the near future.

To carry out the experiments described below, a deflagrating slow explosive charge has been developed for several sizes. This spherical charge is currently made of a central dynamite booster containing the starter in its center. The dynamite booster is surrounded by a thick layer of the main pyrotechnic mixture. The latter is composed of potassium perchlorate, barium nitrate and magnesium powder. The peak pressure released by this type of slow explosive charge is of the order of 500 bars and the mean deflagration velocity is in the range 100 - 300 m/s. These features are thought to be adequate to simulate the SNR-300 h c d a.

All the tests carried out in 1/13 scaled down vessels have been done in simple geometry to allow an easy and sound interpretation of the experimental data leading to the validation of computer codes. Similarly along the execution of the various series of experiments one varied one parameter at a time making then the interpretation task easier and the understanding better. The final shot at larger scale will be a more representative model of the actual SNR-300 reactor and will then include all its major engineered safeguards at a time.

The various series of experiments carried out at small scale (1/13) are as follows :

1) bare charge experiments in overstrong vessels,
2) experiments in overstrong vessels including a perforated dipped plate below the top shield to avoid the liquid impact on it,
3) bare charge experiments in thin yielding vessels,
4) experiments with an outer yielding vessel and an internal yielding skirt,
5) experiments with an outer yielding vessel including an internal yielding skirt and a perforated dipped plate below the top shield.

All these five types of experiments are represented on figure 1 and 2 with the main geometrical dimensions indicated. A more detailed description of these experiments as well as the analysis of some experimental data collected during the course of this programme has already been given elsewhere [1] [2]. But due to the limitations of space we shall limit the discussion of experiments relevant to series 1, 2 and 3 mentioned above.

In parallel with the experimental programme a theoretical programme has been set up to get methods and computer codes available for the interpretation of experiments. Therefore the 2D Eulerian SURBOUM-II computer code has been developed at BELGONUCLEAIRE, while the 2D Lagrangian ARES code has been developed at Interatom. Similarly at Euratom JRC-ISPRA, the 2D Lagrangian REXCO-H code (release 2) was made available and improved.

2. Brief description of the SURBOUM-II computer code

The development of the 2D Eulerian SURBOUM-II code started in 1968 at BELGONUCLEAIRE and went on in collaboration with the UKAEA in the period 1972 - 1974. This code computes the two dimensional fluid flow within a reactor vessel or a model in case of a core explosion and the subsequent deformation of the vessel and includes some internals which have the symmetry of revolution.

The fluid (sodium or water) filling the vessel is assumed uncompressible; this has been assumed chiefly because the pressure released by the charge is low, see above, and because the SNR-300 makes use of a perforated dipped plate below the top shield to avoid the liquid impact on it. The code uses stepwise the Marker And Cell (MAC) method [3]. When the pressure field is known the motion of the fluid is calculated by solving the complete Navier-Stokes equations. The treatment of perforated or porous dipped plates or shells makes use of an empirical relationship between pressure drop and fluid velocity such as compiled in [4].

The present version of the code allows for the deformation of the outer vessels as well as of internal concentric straight shells simulating the shield tank or the core barrel of the reactor. The internal shells may include perforated area having the symmetry of revolution. The calculation of the deformation of the shells is based on thin shell theory including shell inertia and bending moments. The boundary condition at each shell extremity may be selected among 3 types according to the system under consideration. The present version of the code does not allow for a curved bottom yet; the actual vessel bottom is then simulated by a flat bottom characterized by a given axial elasticity, see below.

The code allows also for the coupled axial motion of inertial components such as the top shield (reactor roof), the perforated dipped plate, the core diagrid, the vessel bottom, etc... These components are simulated by means of a mass spring system.

The driving functions of these two mechanical modules, i.e. radial deformation of shells and axial motion of inertial components, are the pressure loadings calculated in the hydrodynamics part of the code; conversely the motion of shells and inertial components are used as boundary conditions for the hydrodynamics part of the code.

3. Derivation of a reference Pressure-Volume relationship

The series of bare charge experiments carried out in overstrong vessels, mentioned above in section 1 has been used to derive a reference pressure-volume relationship for the 1.65 kg explosive charge. Among all the experiments included in this first series, 7 of them correspond to a cover gas volume of 26 l which simulates fairly well the SNR-300 nominal situation. One of these experiments, namely the 108 one, delivers pressure signals which are of good quality and close to the average signals collected for this series. This experiment has then been selected to derive the reference pressure-volume relationship of the charge. The procedure to achieve this goal has already been discussed in details elsewhere [2] for another experiment, namely the 114 one, which is somewhat more energetic than the 108 one. In a few words the pressure-time variation in the charge is adjusted in SURBOUM-II ("inverse way") to fit in the best way the recorded impulse variations at some selected locations within the vessel. However since the SURBOUM-II code does not take into account the fluid compressibility and subsequently the wave transit time to reach the transducer and the wave reflections, the recorded pressure signals are replaced by simplified block diagrams corresponding to the same impulse for each time interval. The elimination of the time variable between the pressure-time and the volume-time curves yields the pressure-volume relationship. One has represented on figure 3 the layout used in SURBOUM-II corresponding to experiment 108 and figure 4 as well as table I give the reference pressure-volume relationship obtained together with an estimation of its uncertainty band. The uncertainty band has been determined as a function of the scattering of the experimental impulses-time curves around the average ones for the series of bare charge experiments carried out in the overstrong vessels.

4. Calculation of experiments with perforated dipped plate

The reference pressure-volume relationship discussed above has been used to perform calculations of the loading on the vessel bottom and lateral wall of experiments of series 2 mentioned in section 1, i.e. including a perforated dipped plate below the top shield. The layout used in the SURBOUM-II calculation is the same as the one given in fig. 3 except that a thin porous plate has been simulated 157 mm below the top shield. The pressure-drop versus fluid velocity relationship has been obtained from [4]. A sample of results which corresponds to a 51.5 % perforation ratio is shown on figures 5 and 6 and compared to the experimental results available. The reader will notice that the overall agreement of theoretical and experimental results is fairly good.

5. Calculation of bare charges in yielding vessels

Calculations have also been done for the third series of experiments mentioned in section 1, i.e. the bare charges fired in thin yielding vessels. The vessel used in the set up was made of mild steel, its thickness was 4 mm and it was held between two overstrong lids as shown in figure 2.

The layout used in the calculation is shown on the left side of figure 7. The explosive charge characteristics is the pressure-volume relationship compiled in table I and shown on figure 4. The mild steel stress-strain relationship has been obtained from measurements made by Mr. Montagnani [5] [2] and an equivalent bilinear law is compiled in table II ; it corresponds to a strain rate of 56 $sec.^{-1}$

The results of the calculations performed with the SURBOUM-II and REXCO codes with the same data have been displayed and compared with experimental ones in figures 7 to 11 obtained from experiment n° 32. The right side of figure 7 shows the space profile of the shell final deformation. The deformation of the shell is important in two regions, i.e. respectively in the vicinity of the charge level since the early time period and in the vicinity of the roof at later time, i.e. when the fluid slug hits the roof. The calculation of the phenomenon during the fluid impact on the roof has not been calculated with SURBOUM-II as the latter is inadequate for this due to the assumption of the fluid uncompressibility.

The agreement between the SURBOUM-II and REXCO-H calculated deformations in the central region is fairly good though the SURBOUM-II results are in the overall greater than those obtained by REXCO-H; this is very likely due to the assumption of fluid uncompressibility built in SURBOUM-II. The agreement between the theoretical curves and the experimental one is globaly also good. Figure 8 shows the variation versus time of the calculated and experimental shell deformation at charge height. The agreement between these three curves is excellent up to the failure time of the strain gauge around 600 μsec (generally occurring beyond 3-4 % deformation). For later times the deviation between SURBOUM-II and REXCO-H increased in this central region. Figure 9 also shows the variation versus time of the calculated and experimental shell deformation in the vicinity of the lower edge of the vessel. The agreement of these three curves is excellent up to the end of the strain gauge record.

The comparison of calculated and measured impulse-time curves is also displayed in figure 10 for the lateral wall at charge height and in figure 11 for the bottom region of the vessel. The reader will notice that the agreement between the two theoretical curves is generally good, i.e. of the order of 20 % for both cases. Nevertheless there is an obvious disagreement between the experimental and theoretical impulse-time curves at charge height which is tentatively and qualitatively explained by too heavy a transducer support mounted (welded) at this very location on the thin vessel. This introduces a local perturbation in the shell motion and a subsequent perturbation in the pressure field. Inversely the agreement between the experimental and theoretical impulse-time curves in the lower part of the vessel is excellent. In this case the pressure measurement was done through the very heavy lower lid (100 mm away of the vessel centerline), and subsequently the weight of the transducer does not perturb the measurement.

6. Conclusions

A reference pressure-volume relationship characterizing the slow explosive charge developed at BELGONUCLEAIRE has been obtained while unfolding pressure records in bare charge experiments in overstrong vessels by means of the SURBOUM-II code. This pressure-volume relationship has been used by the SURBOUM-II code to calculate pressure loading in overstrong vessels experiments including a perforated dipped plate. The agreement between theoretical and experimental results is satisfactory. Furthermore the use of the same pressure-volume relationship to interpret bare charge experiments in yielding vessels has been successful. The agreement between theoretical and experimental value of the vessel deformation are indeed in fairly good agreement.

Acknowledgments

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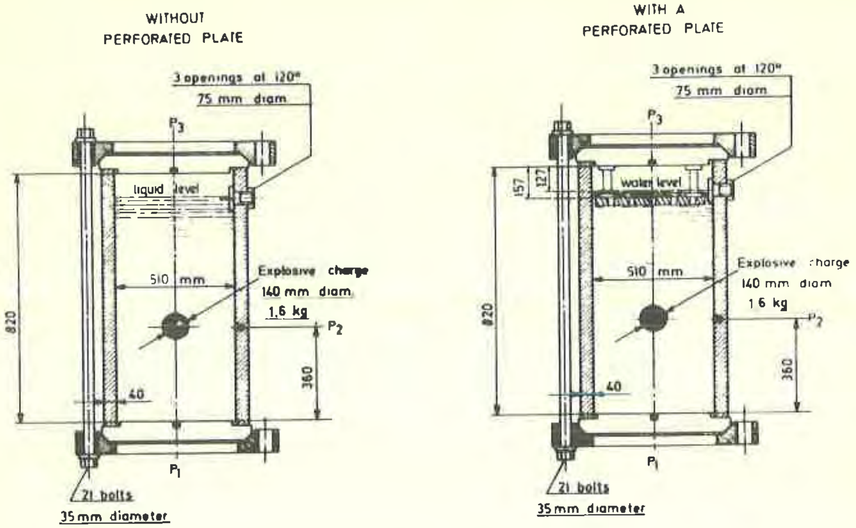
Table I. Reference pressure-volume relationship for 1.65 kg BN pyrotechnic charge

Bubble Volume (litre)	Lower pressure (bar)	Nominal pressure (bar)	Upper pressure (bar)
1.46	376.8	426.8	476.8
1.73	330.8	380.8	430.8
2.33	228.9	278.9	328.9
3.09	149.3	199.3	249.3
4.02	84.	111.7	140
5.07	54.	71.4	89.
100.	0.825	1.1	1.373

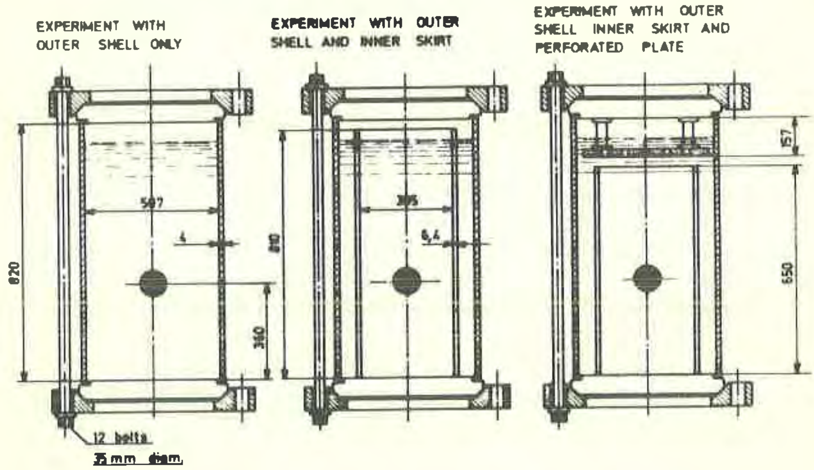
Table II. Stress-Strain relationship for mild steel shells used in SURBOUM-II ($\dot{\varepsilon} = 56\ s^{-1}$)

Strain (%)	Stress (kg/mm^2)
0.214	42.8
7.5	44.47
30	49.63



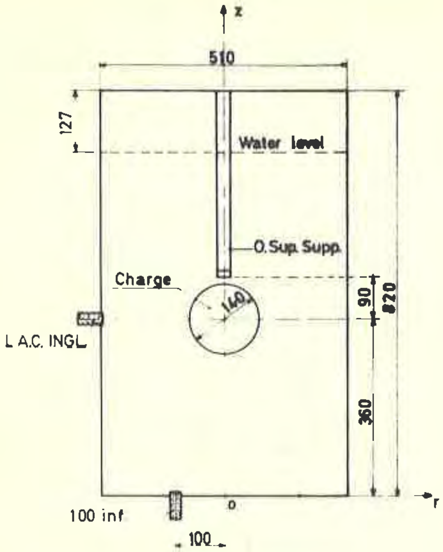
1/13 Scale overstrong vessel

FIG. 1



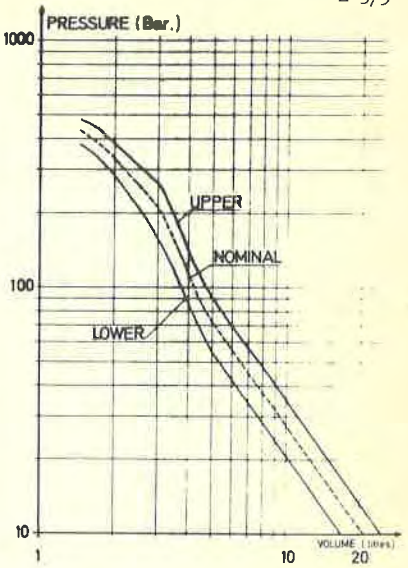
1/13 Scale yielding vessels

FIG. 2



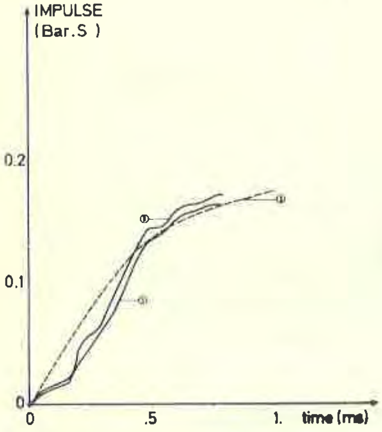
LAYOUT OF EXPERIMENT 108
COVER GAS VOLUME = 2 6 l
CHARGE WEIGHT = 1.65 kg

FIG. 3



REFERENCE P-V RELATIONSHIP WITH UPPER AND LOWER LIMITS

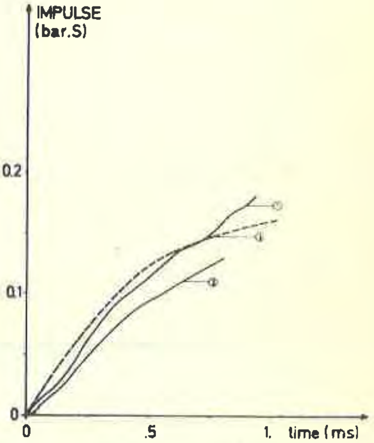
FIG. 4



PRESSURE IMPULSES ON THE VESSEL BOTTOM CENTERLINE

① exp. 22 (r = 51.5 %)
② exp. 20 (")
③ SURBOUM (")

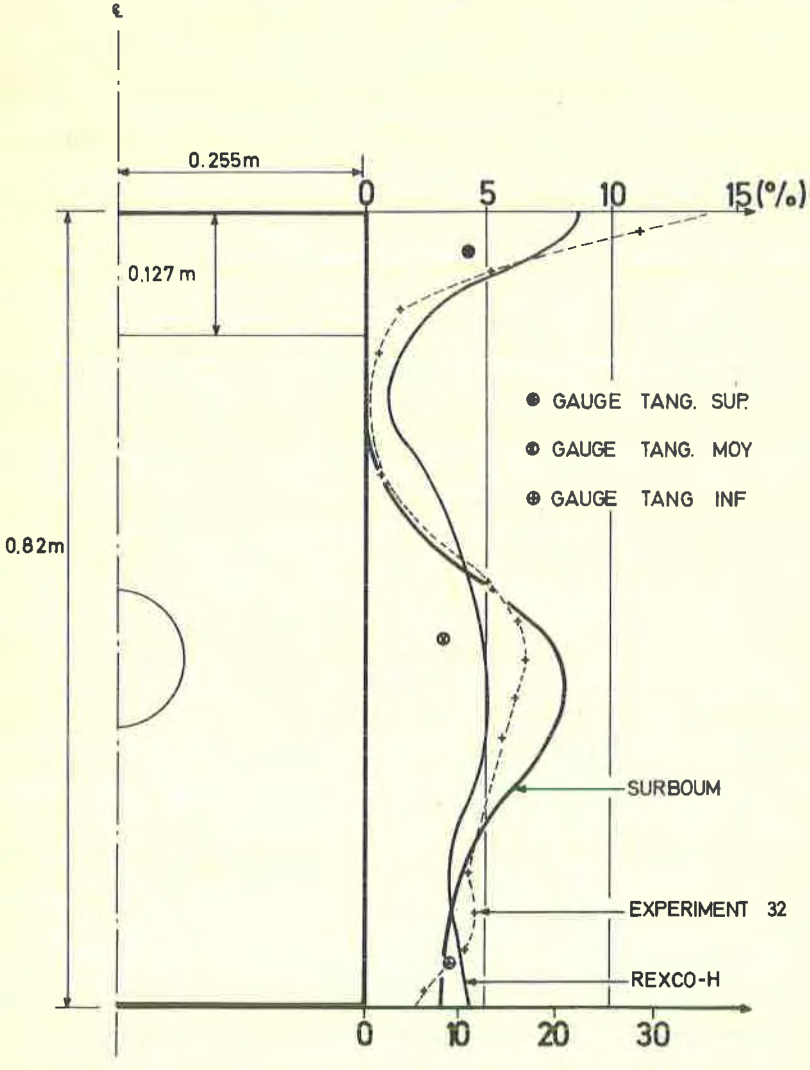
FIG. 5



PRESSURE IMPULSES ON THE LATERAL WALL AT CHARGE HEIGHT

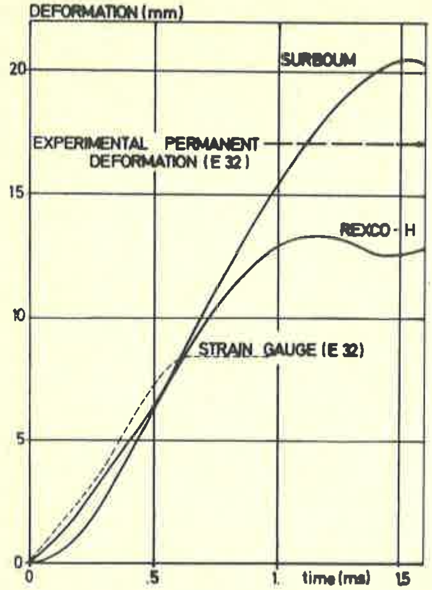
1 exp. 22 (r = 51.5 %)
2- exp. 20 (")
3 SURBOUM (")

FIG. 6



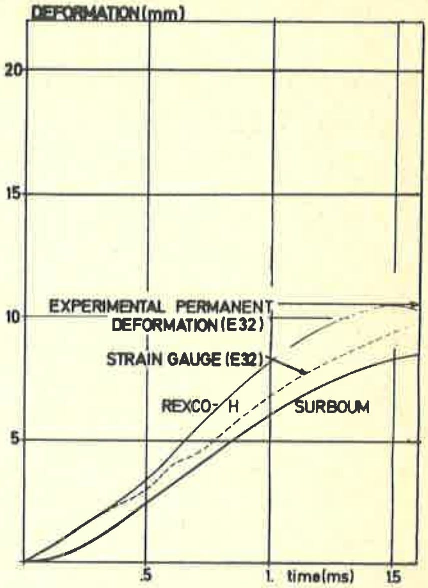
PERMANENT WALL DEFORMATIONS
VERSUS HEIGHT

FIG. 7



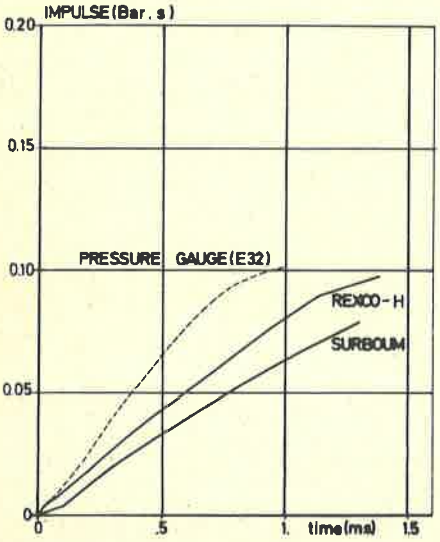
RADIAL WALL DEFORMATION VERSUS TIME AT CHARGE HEIGHT

FIG. 8



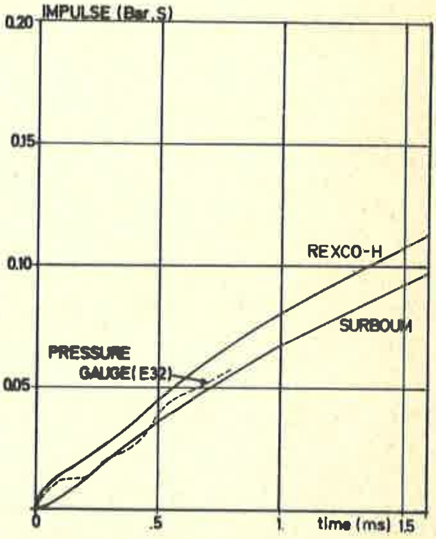
RADIAL WALL DEFORMATION VERSUS TIME AT THE LOWER END OF THE VESSEL

FIG. 9



PRESSURE IMPULSE VERSUS TIME AT CHARGE HEIGHT

FIG. 10



PRESSURE IMPULSE VERSUS TIME AT THE LOWER END OF THE VESSEL

FIG. 11