Status of the RF Superconductivity at CERN

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Abstract

The transfer to industry of the "know how" to build Nb sputter coated Cu cavities has been the major effort of the Superconducting Cavities Community at CERN in the last two years. After having qualified the three contractors for their production facilities and the coating process it turned out that the success rate of all the three was still unsatisfactory (about 50%) for a large scale production. The depth of removal of the Cu surface before coating had to be increased. At present more than 30% of the 168 cavities have passed the bare cavity acceptance test. Seven 4-cavity cryomodules have been delivered and are at various stages of the acceptance test. One has passed the high power test with accelerating fields above the design figure of 6MV/m and it has been installed in LEP during a ten days machine stop end of September 1993, it has been filled with liquid helium and is performing as in the test facility. At the SPS two cavities are routinely operated at 5MV/m each for lepton acceleration and a second 2-cavity cryomodule is under preparation. Power couplers are fabricated by industry and are conditioned in Traveling Wave (TW) and in Standing Wave (SW) to remove multipactor levels. A fraction of the Higher Order Mode (HOM) couplers still show training quenches and changes are being introduced in the cryogenic system to improve the cooling. Moreover it has been found that trained HOM couplers do not show quenches after a warmup.

1. Introduction

The LEP electron-positron collider has entered into operation in 1989 at CERN and it is currently operated at 46GeV per beam for the Z_0 physics. The acceleration system uses 128 normally conducting Cu cavities at 352MHz installed on both sides of interaction points 2 and 6. Already in the initial design it was planned to increase the beam energy above 82GeV for the W^+W^- pair production physics by the installation of 192 superconducting cavities at the interaction points 2, 4, 6 and 8 [1]. It is planned to finish the production of the cryomodules by spring 1995 and to complete the test and the installation in LEP by fall 1995. Physics at W^+W^- energies would then be possible by spring 1996, the year 1995 being dedicated to the running-in of the "new" machine.

An initial production series of 20 bulk Nb cavities has been received and accepted by 1992 [2]. The corresponding 4-cavity cryomodules are being upgraded with movable power couplers and all steel helium gas pipes. The results obtained by sputter coating Nb on Cu for RF applications led to the decision in 1991 to order 168 of such cavities from industry [3]. The cavities are to be delivered assembled in 4-cavity cryomodules, fully equipped with tuners, power couplers (MC) and Higher Order Mode (HOM) couplers. The cavity fabrication process has been described elsewhere [3, 4].

2. Bare cavity test

The cavities are tested at CERN after the sputter coating to check the superconducting properties of the film, the Q_o vs accelerating gradient being the most relevant one. The results of the three firms are sensibly similar, Fig. 1 shows some typical cavity results. The number of the defects, measured with a temperature mapping system, the temperature dependent Q-value (Q_{BCS}) and the temperature independent residual Q-value (Q_{Res}) are routinely verified [5]. It appeared soon after the series production was started, that the success rate of the cavities was too low to be acceptable, Fig.2a, and that the number of defects detected by temperature mapping was high [5]. In nearly all the cases they were caused by insufficient adherence of the coating to a contamination on the copper underneath.

It turned out that the copper surface was damaged to a depth of about 100µm [6], and that if this damaged layer is not completely removed, pits and microcavities are produced on the surface which retain chemicals even after demineralised water rinsing. The copper crystal structure is most damaged at a depth ranging from 80 to 120µm. The electropolishing has been applied in two steps and the rejection rate dropped to about 15% with one company. For the first coating of another company, although the number of defects was much reduced, the Q_o showed a strong dependence on the RF field amplitude. The Q_{BCS} and the Q_{Res} were lower (8.10^9 and 10^{10} resp.) and the sensitivity to the ambient magnetic field enhanced. The subsequent coatings of the same firm were all good. This behaviour was traced to a shorter bakeout and to a forced cooldown before coating. The procedure has been modified since and the few cavities produced show encouraging results.

3. Four-cavity Modules

The accepted bare cavities are equipped with a welded He-tank and the tuning system of three bars (combined magnetostrictive and thermal action) mounted in a cylindrical insulation tank forming a unit. Four of those units are assembled to a four-cavity module and foreseen with end cones, piping and cabling. Two HOM couplers and one main coupler are added in the clean room to each unit.

3.1 Bulk Nb modules

Modules made of bulk Nb cavities have fixed MCs at 30^o from the vertical axis. They have been assembled at CERN, but problems have been encountered with high power operation (heating and sparking in the MCs). The Q values showed also signs of degradation in some cavities, Fig. 3a.

In the mean time variable MCs [cf. below] have been developed with two diagnostic ports close to the ceramic window. They allow to monitor the electron activity and the local vacuum near the ceramic window; it is thus possible to identify the multipactor levels .

Module CERCA4, equipped with such couplers, went through the whole test chain (low power at critical coupling, conditioning with tetrode to 15kW SW incident power, final operation with klystron) and has been installed in LEP [7]. During high input power conditioning the power was risen in a way such as to keep the local vacuum at the window below 3.10^{-8}mbar. The procedure required about 40h to reach the 5MV/m level.

Based on the results obtained, a consolidation program has been started to upgrade all the cavities with movable MCs, install cooled RF cables for HOMs, replace the radiation shields by additional superinsulation layers and modify the piping to eliminate all copper pipe connections brazed in situ. An ultraclean rinsing with high pressure and low pressure water is performed after mounting of HOM couplers.

3.2 Nb coated modules

Module 3001 arrived at CERN in December 1992; until now seven modules have been received in total, all manufacturers having delivered at least two modules (2+3+2). In addition, each manufacturer has already the following module in the pipeline close to delivery. Some typical results of 4 modules tested so far are presented in appendix A.

Module 3001 had a vacuum accident during transport, which obscured the original module performance. This module was still equipped with HOM couplers of type 5a [8] having a narrow notch, difficult to tune. One cavity could not be fully tested due to insufficient tuning of one HOM coupler. HOM couplers showed quenches but could be processed to hold the maximum cavity field. It has been sent back to the firm for repair and it is now under test equipped with HOM couplers type 5c.

Module 2001 could be processed above the desired 6 MV/m for all cavities, however, two cavities were slightly below the specified Q-value; the module was accepted as prototype. This module - equipped with 8 HOM type 5a - was plagued with two quenching HOM couplers which could finally be processed. To test also the main couplers under power as necessary in LEP, a tetrode (without circulator but adapted distance to the cavity) was connected. Using the local vacuum in the coupler as steering quantity, the field was risen above 6 MV/m for three cavities, powering one cavity at a time. The local vacuum was limited to $<1.10^{-7}$mbar and the procedure lasted about 12 h per cavity. On the fourth cavity a leak developed during processing in one HOM ceramic window between the liquid He volume and the insulation vacuum. This leak increased the pressure in the insulation tank such that the LHe was evaporated quickly and the safety valves opened, the rupture disks being preserved. Very probably a flash in a connector on the HOM coupler had caused the overheating. This accident confirmed also the decision to suppress the (older design) HOM coupler 5a.

The same module 2001, Fig. 4a, has been equipped with 8 HOM couplers type 5c , having the advantages of a single ceramic window between the cavity and insulation vacuum and a wider filter notch - thus easier HOM filter tuning. The module showed 2 quenching HOM couplers (on partly different HOM locations) and these quenches were voluntarily preserved to use the module for several studies on the HOM cooling circuit. Actually the module is under preparation for a final test of the improved cryogenic layout using coaxial pipes for LHe 'injection'into the HOM couplers and gas-cooled RF cables for HOM power evacuation.

The module 2002 showed a better performance than module 2001., However, one cavity was still slightly below the specified Q-value at high field, Fig. 3b . Two HOM couplers quenched but could be processed. The module was tested with klystron and finally installed in LEP (see below).

Module 1001 had two cavities within specification after only short processing, Fig. 4b . A third cavity showed a Q-value significantly under specification at low and high field, thus it is believed that a contamination happened during assembly. The last cavity was plagued by a HOM quench which could not be overcome despite many different processing methods. Thus also this cavity - limited by electron loading - could not be processed to specifications. The module was warmed up and, after the following cooldown it was possible to process the HOM quench slowly away allowing then also the cavity to be He-processed to specifications. The cavity with low Q - an end cavity - will be taken off from the module and water rinsed at the manufacturer. Before reassembly with the module the cavity will be tested as a single cavity unit.

Module 3002 showed one cavity within specifications after very short processing, the other three being plagued by pertinent HOM quenches. One HOM quench could be processed to 7 MV/m and the cavity is also within specifications. The second quenching HOM resisted permanently untill now and the third HOM had a temperature probe with poor thermal contact making the recovery control very slow and the processing extremely inefficient. The gauge has been fixed since and the conditioning restarted.

It was observed on several modules that the end-cavity at the liquid inlet side of the module had a lower Q-value than the others. To check if this cavity, the first to cool down, traps more gas than the others during the fast standard cool down, this module was warmed up and cooled down very slowly. The performance of all cavities had not improved. At present the module is warmed up a second time to follow the experience of the previous module, where a warm up after an initial period of processing allowed a better progress with quenching HOMs.

Module 2003 was delivered on request of CERN without HOM couplers to allow a quick test of the assembly quality of the module. The two central cavities were on specifications very quickly, but both end cavities were plagued with strong electron loading. After a long period of processing these cavities could be brought to specifications.

Concerning cabling, 3 broken connections were detected among all the tested modules. All tuners without exception worked on specification. The cavity frequencies were not very precise for the first module of each manufacturer since setting is different due to small differences in manufacturing procedures. However, the last two modules delivered show a very good frequency adjustement for 3 cavities, only one cavity frequency being too high resp. too low, the reasons are under investigation.

As conclusion it can be said that the first modules received were not perfect but - except a real vacuum or contamination accident - could be pushed up above the desired 6 MV/m. With slightly increased RF losses these modules could be used in the machine - apart from the remaining coupler problems. Another positive aspect is the clear progress seen with the 3 modules from one manufacturer, going from 2 to 3 and then to 4 cavities fully in specification.

3.3 High power test

The modules, before installation in LEP, undergo a high power test in a facility that replicates one of the LEP RF units. One 1.3MW klystron is used to feed up to three 4-cavity modules. Module CERCA4 (bulk Nb, movable power couplers) and module 2002 (Nb coated Cu, movable power coupler) have successfully gone through the high power test and have been installed at Pt2 and Pt6 of LEP, respectively [7].

The power couplers have been equipped with diagnostic ports for vacuum gauges and electron probe antennas. The conditioning process was determined by the pressure at the ceramic window, that was kept below 2.10^{-7}mbar, at the beginning of the conditioning, and then put to 3.10^{-8} up to the maximum incident power of 25kW per cavity. The conditioning time was 30 hours to go from 2MV/m to 5MV/m (for Nb) and 6MV/m (for Nb/Cu) respectively . The use of the electron current (up to 100μA) as conditioning criterium proved to be impossible as the current values were too erratic. After operating the cavities at the nominal field for many hours the MCs needed reconditioning. This took, however, few power cycles. High radiation levels (up to 90kRad/h on module CERCA4) have been measured at the beam tubes. The activity did not diminish with operation time [7].

3.4. Experience in LEP

The accelerating field has been limited on purpose to 3.5MV/m during physics runs in order to not disturb the circulating beams in case of voltage trip. During MD sessions module CERCA4 has accelerated beams with fields up to 4.5MV/m.

Module 2002 has reached 6MV/m, 40MV in total, with a beam of 5mA. The MC deconditioning has been encountered too and dummy ramps are performed between physics runs to recondition the MCs.

Fig. 5 shows module 2002 installed at Pt 6 of LEP, connected to the waveguide system and to the cryogenics lines.

4. Power Couplers

Power couplers with varying coupling strength of 3.10^9 to 5.10^5 have been developed at CERN [8]. Since then a contract has been placed with industry (**) for a series production and 140 units have been delivered and are undergoing the high power conditioning.

The high range in Q_{ext} of the power couplers finds its usefulness in three different areas:

- the measurement of Q vs. Eacc at the module acceptance test, at each critical phase of module conditioning and at any time in the accelerator, to monitor cavity degradation, all without breaking the cavity vacuum;
- the correction of the coupling scatter of cavities installed in the accelerator, shown by the fixed couplers and seen in other laboratories too;
- the matching to the beam current intensity can always be insured.

Two couplers at a time are conditioned on a bench up to 180kW TW mode and up to 50kW incident power in full reflection. Two diagnostics ports are available to monitor the internal electron activity and the vacuum level near the ceramic window during conditioning and operation.

(**) SICN-F

It has been observed that operation at high power levels reactivates low power multipactor thresholds and that several iterations with cycling of RF power are needed to overcome this deconditioning effect [7,9]. The power coupler conditioning benches have a resonant cavity as coupling element and allow the conditioning of fully assembled couplers, both the inner antenna and the outer coaxial conductor, under SW and TW conditions. It is foreseen to assemble and disassemble the coupler in class 100 clean room. The benches will be also used to identify the multipacting zones.

5. Higher Order Mode Couplers

During cavity conditioning about 25% of the HOMs showed training quenches that necessitate a fast switch off of the RF power. A thermometer on the cooling pipe of the inner post is used as a quench detector with a response time of 300-700msec. The fundamental mode power leakage is sensed too and it is used as an interlock, indicating a detuning in the coupler itself.

Two main sources are conjectured:

- field emission, with origin in the cavity, as indicated by the drop of Q vs. Eacc, in the majority of the cases ;
- multipactor within the coupler that is enhanced by adsorbed gases (e.g. He gas during He processing)

Quenches can be trained away by He processing at fields just below the threshold in case of field emission and by simultaneous application of HOM power (at present 506MHz, 200W).

The HOM couplers had been designed to provide mode damping for beams of 16 bunches. A recent decision to not exceed 8 bunches per beam gives the possibility to launch the next series production with damping action reduced by a factor of 2. The penetration into the beam tube will be shorter by 10mm , thus reducing the coupling to the fundamental mode and the area exposed to field emitted electrons. It is expected that this will diminish the frequency of training quenches.

To go a little further with this line of thinking another HOM has been designed. The present hook type exposes those part of the HOM that carry high current in the fundamental mode to field emitted electrons. The new geometry variant which hides those parts is in a prototyping stage, Fig. 7.

Another approach to reduce the quench rate could be to improve the cooling and the thermal conductivity of the HOMs. A 5c type Nb coated Cu coupler has been completely developed and manufactured by industry (*). It has been successfully tested at CERN. Nothing can be said yet about the quench statistics. It has not yet been decided whether this development will be pursued.

6. Cryostat

There are no major changes to the cryostat with power couplers at 45^{o}[3]. The internal LHe and gas He piping is all TIG welded stainless steel, to eliminate the risk of cold leaks to the insulation vacuum.

The recent results of HOM coupler conditioning have indicated the need to intercept the static and the dynamic heat input from the RF cables,

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(*) SICN - F

1-2W and 5-10W respectively for cable length around 1m. Two RG165 type cables are needed to extract up to 200W of power from each HOM coupler. Counterflow cooling will be implemented by clamping each cable at 8 points to a steel tube carrying 0.025-0.05g/sec of He gas of 4.5K. The exit gas temperature is the 15-40K range, and the gas will subsequently be used for cooling the beam tube tapers, the tuning system and the power coupler antenna.

At the same time the temperature probes have been rearranged. Temperature gauges are now installed also on the HOM cables, the intercavity bellows and the beam tube tapers. Calculations on beam tube propagating HOMs indicate that more than 20W may eventually be absorbed by each taper at the end of the 4-cavity cryomodules [10]. Experimental confirmation of these estimations is expected from the modules installed in LEP and may force to upgrade the taper cooling.

The heat losses at zero RF of the 4-cavity cryomodules are shown in table 1. Module 1001 and module 2002 have been equipped during conditiong tests with thin HOM cables having low thermal conduction to simulate gas-cooled RF cables.

Module	Type	Losses [W]	HOM cables	comments
CERCA4	Nb	84	RG141, long	
1001	Nb/Cu	90	KO2252D	thin cables for test reduced HOM superinsulation
2001	Nb/Cu	104	RG165, short	uncooled cables no HOM superinsulation
2002	Nb/Cu	77	KO2252D	thin cables for test
2003	Nb/Cu	63	no HOM	uncooled cables no HOM superinsulation
3001	Nb/Cu	123	RG165, short	

Table 1 : Static heat losses

7. Cavities in SPS

At present one 2-cavity cryomodule is routinely operated at the SPS for the acceleration of lepton for LEP. The cavities are of the LEP type, one is made of bulk Nb while the second one is Nb coated Cu. Both have been fabricated at CERN. The two cavities are powered by individual 50kW tetrode tube amplifiers, and are operared at 5MV/m each in pulsed mode, thus providing in total 16MV of accelerating voltage out of the 32MV required for lepton acceleration. A dedicated cryogenic plant provides 400W of cooling power at 4.5K. The SPS is also a 450GeV proton accelerator with intensities of 3.5 10^{13} particles (300mA). An active feedback dumps the cavity shunt impedance in the fundamental mode passband [11]. More than 40000 cavity-hours of operation have been accumulated till now without noticeable permanent degradation of the RF performances. It is planned to add another 2-cavity module by spring 94 to improve the operational reliability and to provide higher injection energies for LEP.

In August 1992 a vacuum accident occured in the SPS. The proton beam was lost and it opened a leak of some 1000mbar l/sec of air some 400m away from one cold SC cavity that was equipped with one fast and one slow vacuum valve on the accident side and by one slow valve in the other side. The setting of the vacuum pump trip levels and the alarm logic were such that the sector valves closed too late and that more than 1000 standard liters of air (1.3Kg) entered the cold cavity, forming a layer of solid air about 0.3mm thick. The cryogenic plant was stopped by the strong evaporation of LHe, and the cavity had to be removed to restart the accelerator within a reasonable time. The cavity has been tested again, and although it is impossible to measure precisely the Q vs. Eacc with the present fixed power coupler, it has been possible to raise the field to 5MV/m within a limited conditioning time and the LHe evaporation rate did not show abnormal values. We conclude that the Q value was not strongly degraded.

8. LHC cavities

The RF system for the Large Hadron Collider (LHC) project of CERN will consist of 8 superconducting single-cell cavities at 400MHz, each powered by its own klystron [12]. They will be arranged in 2 strings of 4 cavities, symmetrically placed around an interaction point.

In order to gain experience with SC cavities operating with high proton beam currents, it has been decided to install in the SPS a prototype LHC cavity powered by a 50kW tetrode amplifier. The fabrication process is the same as the Nb coated Cu cavities for LEP. The Cu thickness is of prime importance as it defines the stiffness of the cavity to the tuning and the resistance to buckling. The first prototype, made out of 2mm Cu, buckled partly during tests at 4.2K, but did not collapse. It was decided to continue with the fabrication and the assembling in order to gain experience with the cryostat, the HOMs and the power couplers. The cavity reached a Q of $6.\ 10^9$ at low field and $3.\ 10^9$ at 6MV/m.

Beam stability calculations for the SPS show that a modest amount of HOM damping is required. It can be obtained by two couplers mounted on the beam tube on each side of the cavity. The tuning system for LHC requires a fast tuning over at least 25kHz (150μm of stroke) for the compensation of the beam loading. The present LEP cavity tuning system provides only 5.5kHz at maximum using magnetostriction on 2m long nickel bars. This is sufficient for a first test in the SPS, but it is not sufficient for LHC and a new tuning system has to be designed.

It is planned to install one cavity in the SPS in the 1994 shutdown.

9. Higher frequency sputter coated cavities

Studies are being pursued in collaboration with other research laboratories on the developement of coatings for higher frequency cavities. At these frequencies cheap fabrication techniques like hydroforming have been demonstrated for single cell and for multicell cavities [13].

Low field Q-values of 10^{10} and accelerating gradients of 16MV/m have been obtained in single cell cavities. However, the Q value at maximum field is 10^9 due to the decrease of Q with accelerating field, the reason of which is under investigation , Fig. 6, [14].

10. Nb coating and Cu surface studies

A considerable effort has been devoted to understand the physics underlying the behaviour of the Nb coated cavities so as to possibly reduce the Q degradation with increasing the accelerating field. Such degradation seems to originate from Nb crystal boundaries and it should be possible to reduce it by growing films with a lower concentration of grain boundaries.

A systematic optimisation of cavity preparation indicates that Nb coatings characterised by RRR in the range from 25 to 30 should be feasible. This should considerably increase cavity Q at accelerating fields higher than 3MV/m [15].

11. Inspection of cavity surfaces

An instrument has been designed and constructed at CERN to allow surface analysis inside standard LEP cavities. The instrument consists of a measuring head (equipped with scanning electron microscope, Auger electron spectroscopy and scanning Auger mapping) mounted on a computer controlled movable arm contained in an UHV system. By means of this facility the surface defects, previously localised inside the cavity by temperature mapping during RF testing in subcooloed Helium, may be analysed in terms both of surface morphology and chemical composition. The instrument is now operational and cavity inspection is presently in progress.

12. Collaboration with TESLA

In the ongoing collaboration with TESLA CERN has contributed to the definition of the TESLA Test Facility. CERN has partecipated in the design considerations for cavities, cryostat, RF-couplers, RF-power system, clean room, chemistry, surface treatement, clean handling, and assembly of cavities, The construction of the ultraclean high pressure rinsing cabinet is done at CERN.

13. Conclusion

The series production of Nb coated Cu cavities by industry is possible and it is well under way. During the setting up of the production it became necesary to further improve the coating process and this gave the opportunity to gain a better insight into the coating technology. The Nb coating know-how has also been transferred to higher frequencies where cheap hydroforming fabrication techniques are available.

The assembly of large cryomodules under strict dust-free conditions has started in industry. One module has been accepted and installed in LEP for operation. Two module per month are being delivered. A fraction of the HOM couplers show training quenches related to electron activities in the cavity or in the coupler itself. Ways to overcome these limitations are under study. The power couplers show deconditioning after operation at high power levels and power cycles can be applied in order to overcome the (multipactor) thresholds.

Acknowledgements

The competence and the skill of the staff both of CERN groups and of the contractors have been a key issue for the advancement of the project. The Cryogenics Group should be mentioned in particular as it has restlessly supplied the large quantities of LHe necessary for the cavity tests.

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Appendix A

Module/ Cavity	Frequency [MHz]	Emax [MV/m]	Q(6 MV/m) [10^9]	Static losses [W]
1001				90
102	352.237	6.9	3.2	
103	352.194	7.3	4.0	
104	352.202	7.1	4.0	
109	352.180	6.0	1.6	
2001				104
208	352.210	6.9	4.0	
207	352.215	7.3	3.7	
203	352.214	6.4	2.5	
205	352.192	6.3	2.4	
2002				77
209	352.200	7.3	3.7	
214	352.203	7.4	3.6	
214	352.203	7.5	3.9	
213	352.197	7.1	2.8	
2003 (*)				63
202	352.187	7.1	3.2	
212	352.164	7.9	3.6	
210	352.172	8.2	3.6	
215	352.181	7.1	3.4	
3001				123
303	352.195	5.7		
304	352.215	5.6		
302	352.210	HOM limit		
307	352.199	5.0		

Results of measurements of Nb/Cu modules.
(*) Module 2003 has been tested without HOM couplers

Figure Caption

Fig. 1 - For each manufacturer of Nb coated cavities three typical curves: one with largest Q-value at 6MV/m, one with lowest Q at 6MV/m, and one with largest accelerating gradient.

Fig. 2a - Number of accepted cavities compared to the number of coatings performed (per quarter)

Fig. 2b - Total number of accepted cavities

Fig. 3a - Module CERCA4, Q-values of single cavity tests (diamond) and of 4-cavity module (square)

Fig. 3b - Module 2002, Q-values of 4-cavity module test.

Fig. 4a - Module 2001, Q-values of bare cavity test (white squares) and of 4-cavity module test (black diamond)

Fig. 4b - Module 1001, Q-values of 4-cavity module test

Fig. 5 - Module 2002 installed in LEP at Pt 6.

Fig. 6 - Nb coated hydroformed Cu cavities at 1.5GHz

Fig. 7 - HOM type 5m

Typical Q [1E9] vs Ea [MV/m] of accepted Nb/Cu cavities from industry (vertical test)

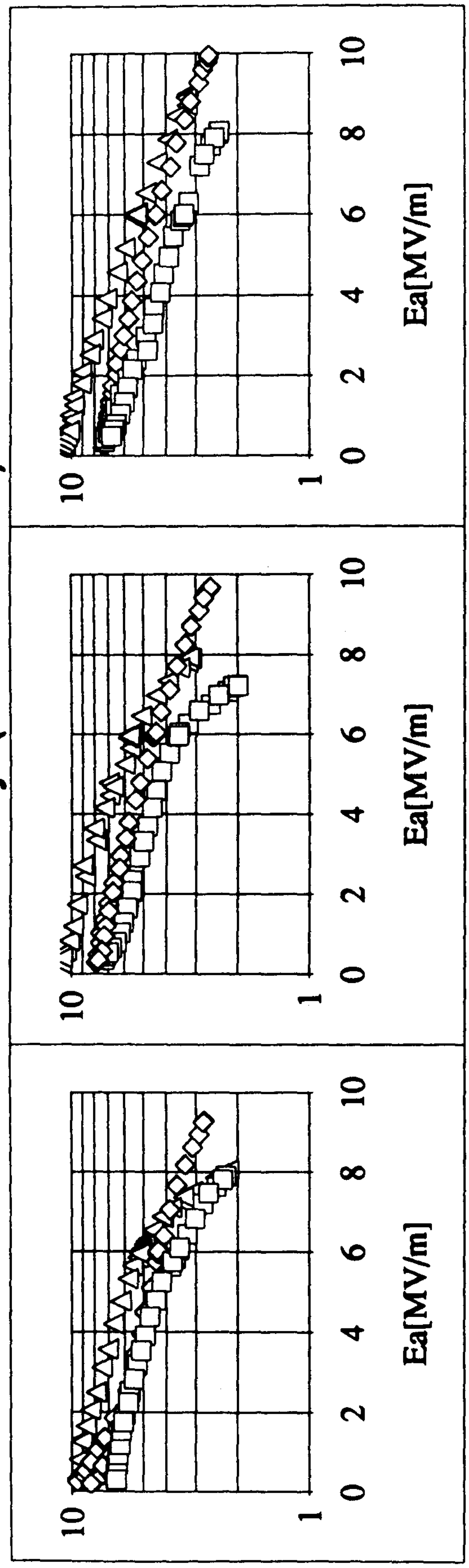


Figure 1

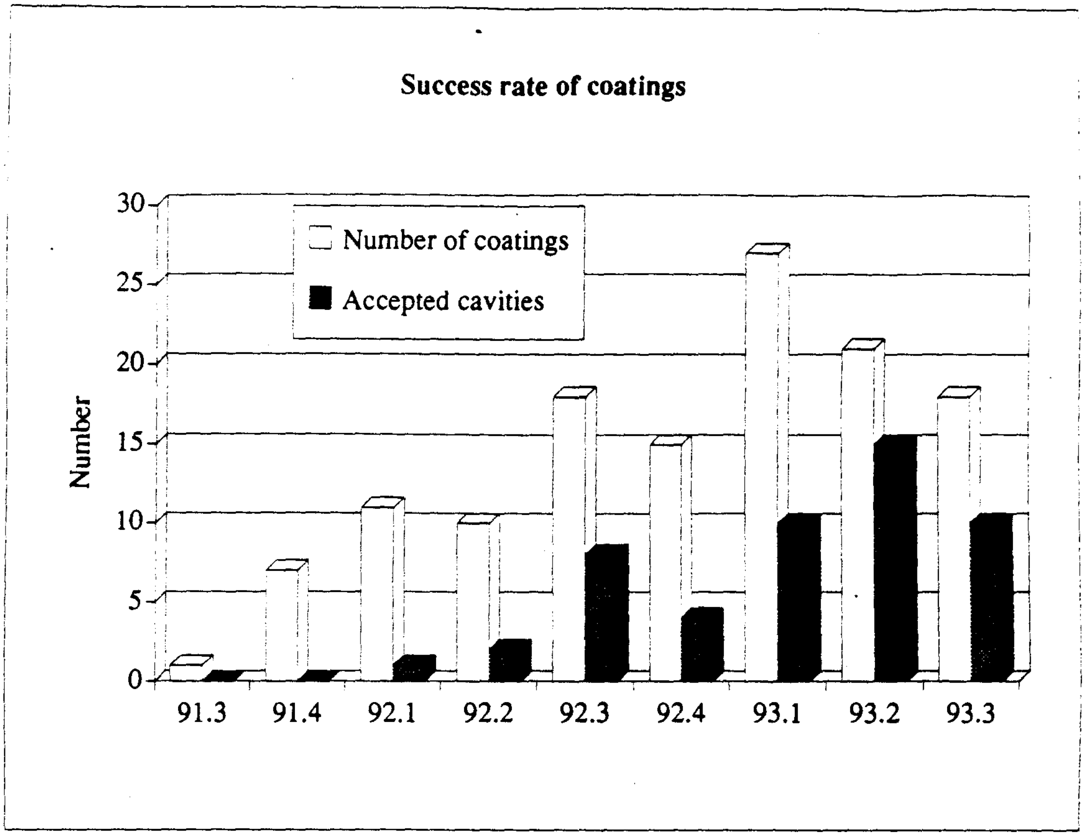
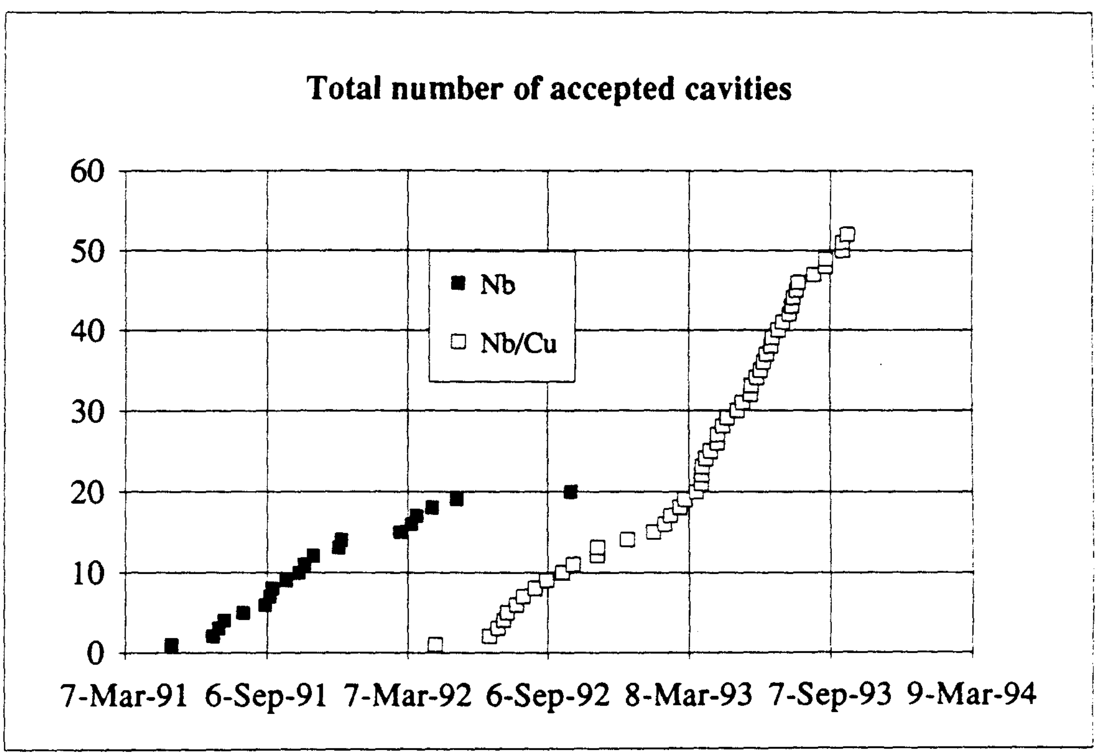


Figure 2.a



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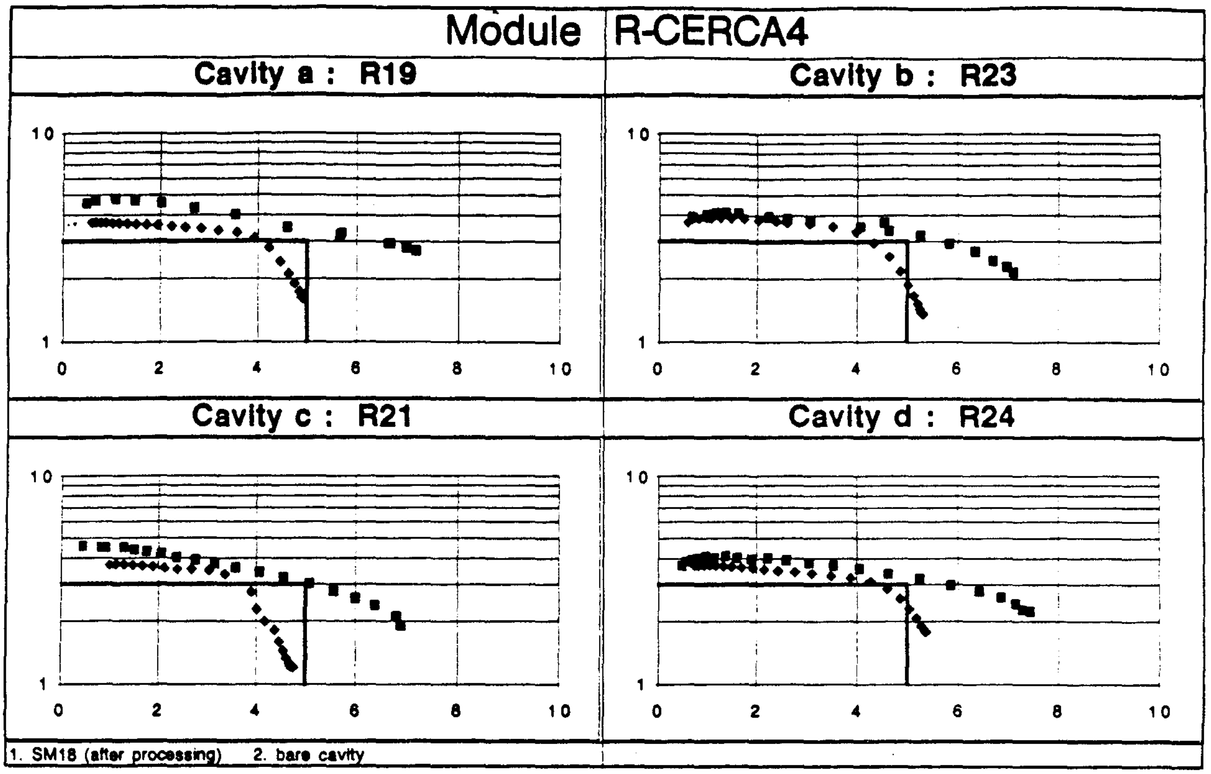
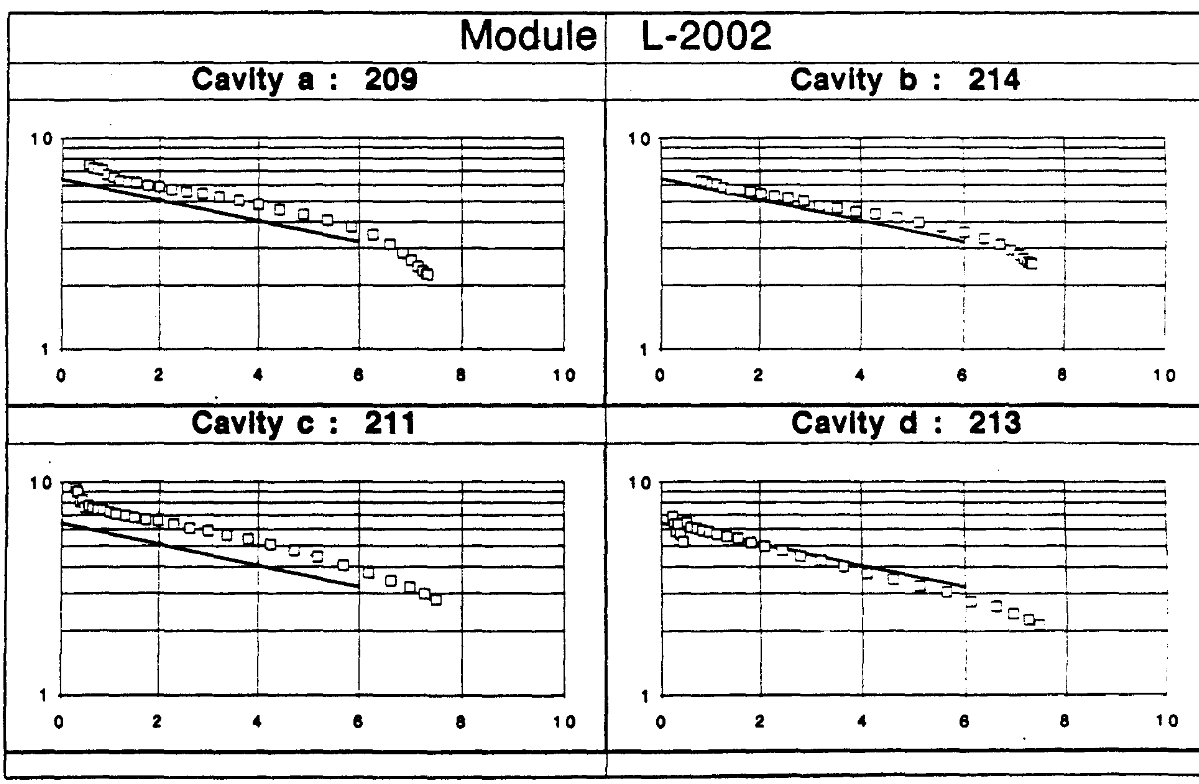


Figure 3.a



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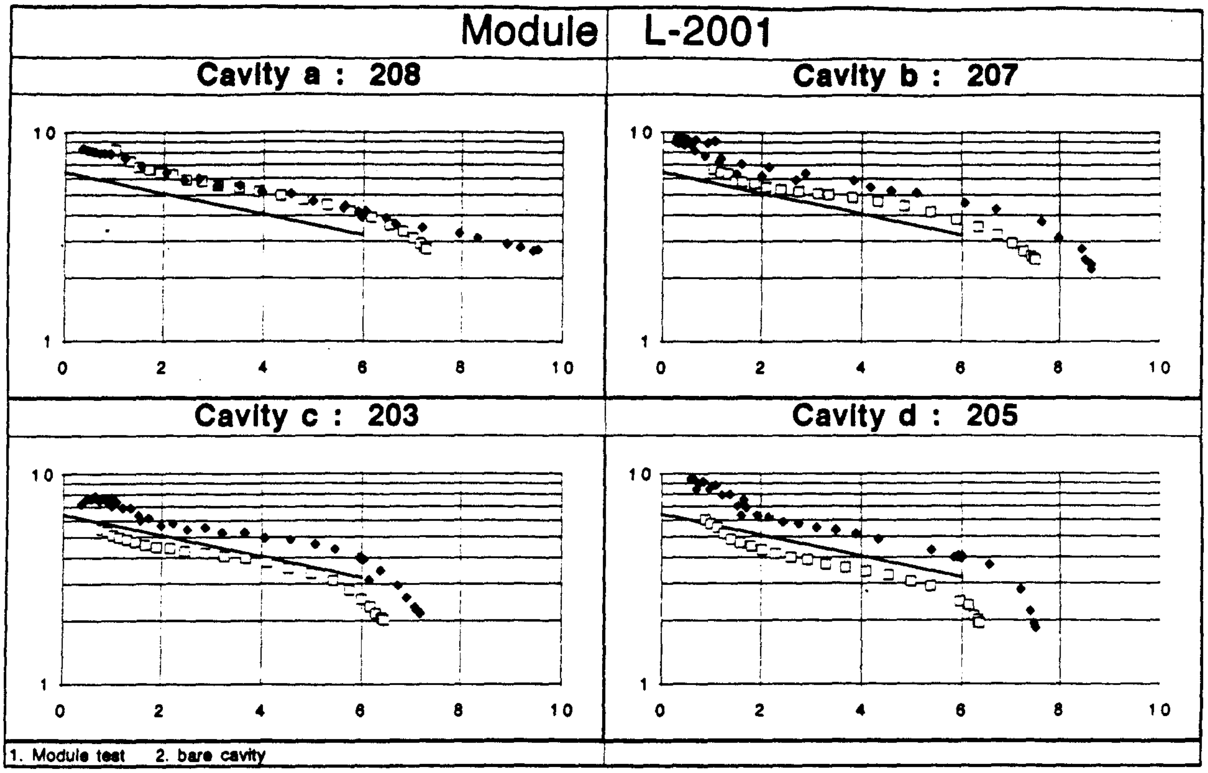

Figure 4.a

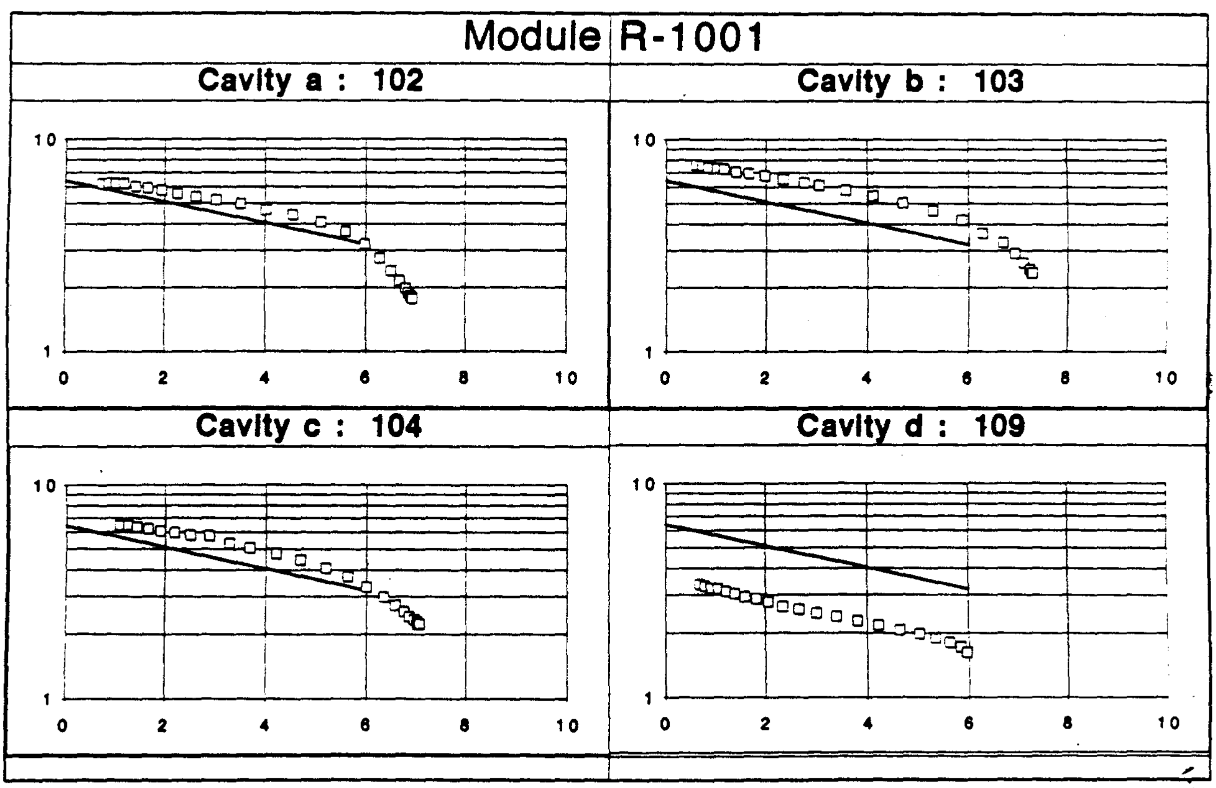

Figure 4.b

Figure 5

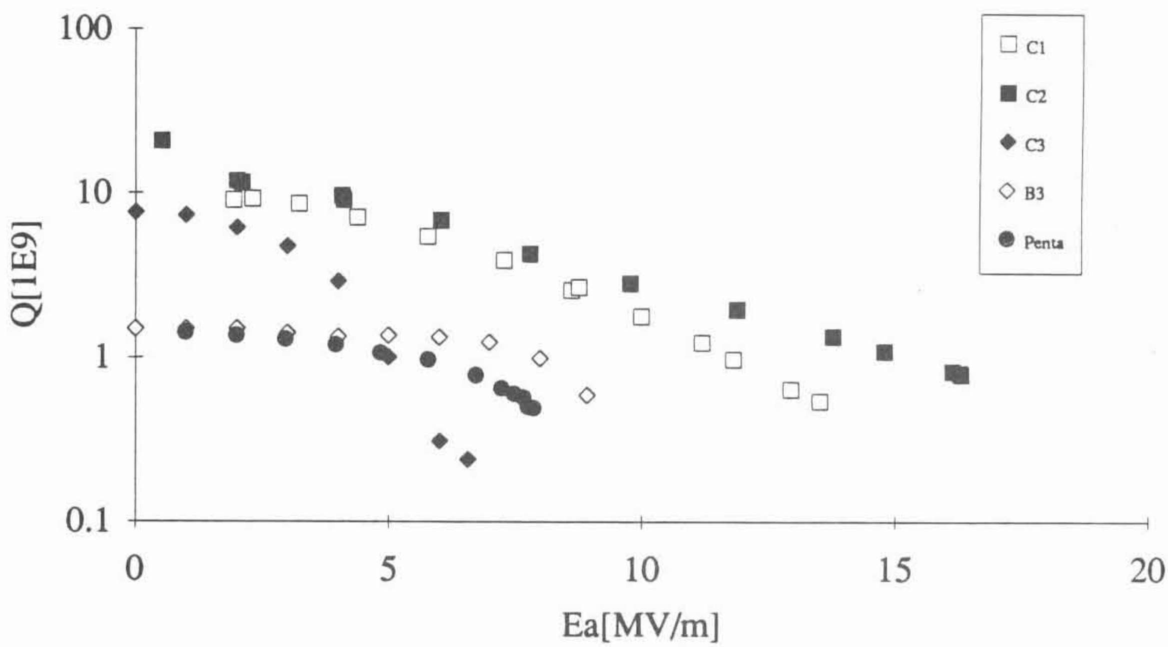

Figure 6

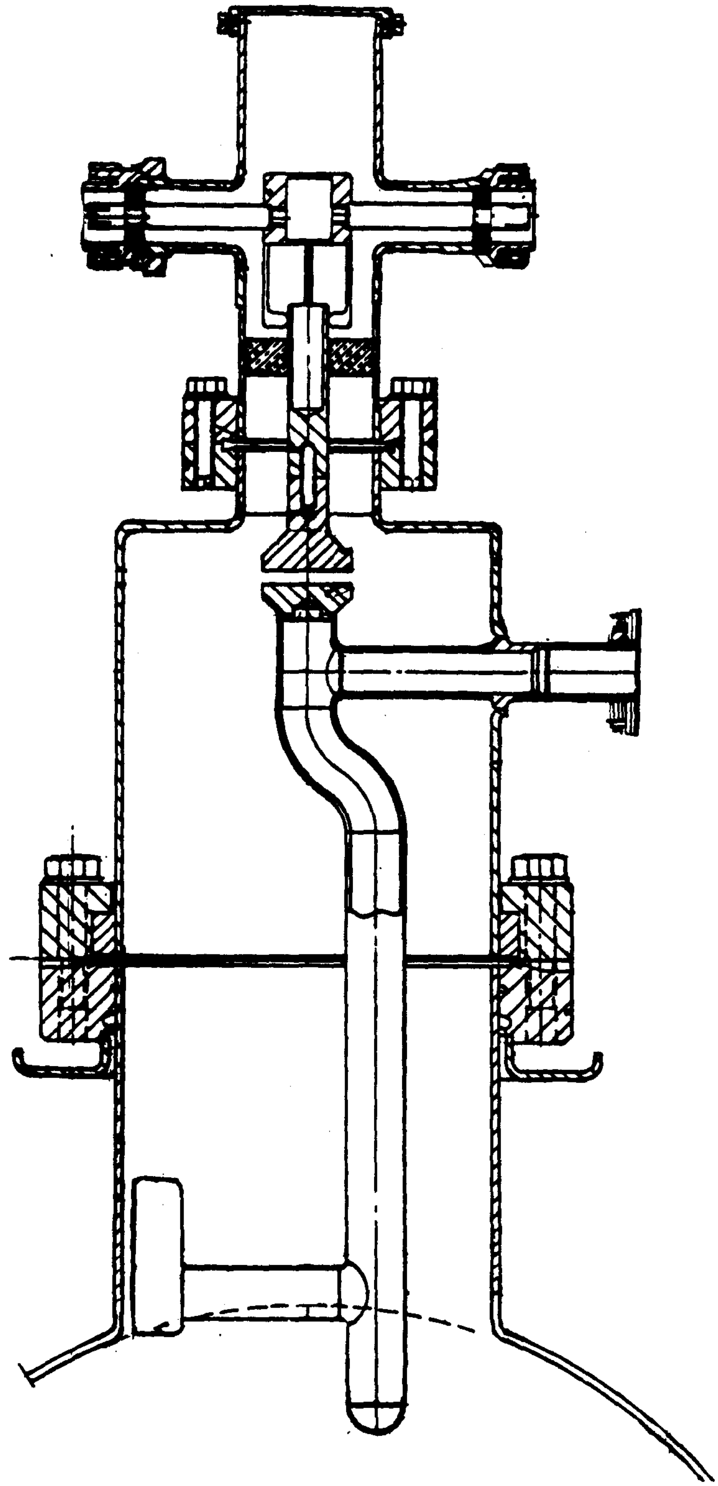

Figure 7