1 INTRODUCTION - ICET BACKGROUND, OBJECTIVES AND PROGRAMME

The purpose of most laboratory tests on cavitation erosion is to predict material performance under cavitation attack in a full-scale hydraulic machine or structure. As the course of erosion is generally known to depend essentially on cavitation impacts distribution [6], reproduction of this distribution in laboratory may be considered a condition of reliable quantitative assessments. In fact, such a procedure is usually not executable. It is also not desirable due to unacceptable elongation of the test duration. Therefore, cavitation resistance of materials has to be assessed basing on tests with cavitation intensity much higher than that in the field.

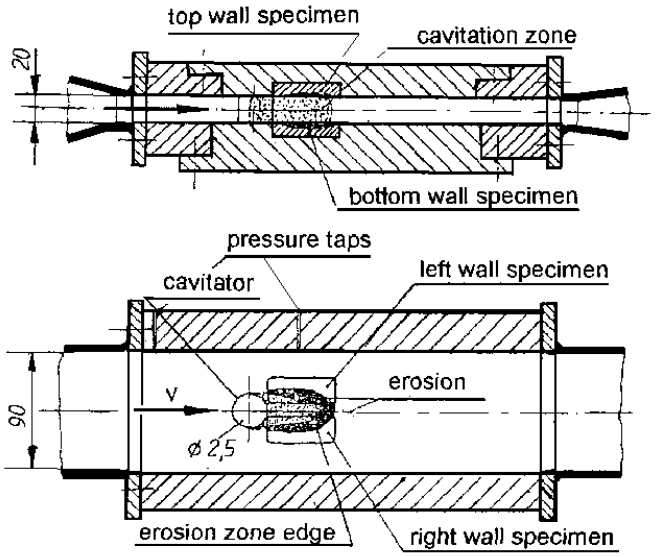

Fig.1 Cavitation tunnel in the Hohenwarte II Pumped-Storage Power Plant (Germany**) - test chamber with a cylindrical cavitator and 4 specimens**

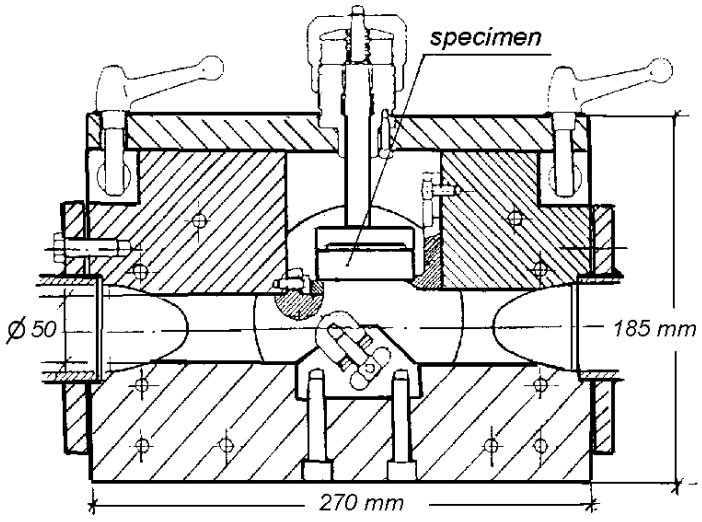

Fig.2 Cavitation tunnel at the University of Hannover (Hannover, Germany**) - Erdmann-Jessnitzer test chamber with a system of barricades**

Cavitation conditions resembling pretty closely those in the field can be created at flow rigs - cavitation tunnels and rotating disk facilities. Various flow obstacles (cylindrical bolts, wedges, venturis or barricade/counter-barricade systems) are applied to generate cavitation in tunnels (Fig.l,2). Intensity of cavitation generated in such a way is rather low. However, due to easy access to the flow-confining walls, cavitation tunnels are often used for fundamental research on cavitation impingement and erosion.

Cavitation of much higher intensity than that in cavitation tunnels can be attained at rotating disk facilities (Fig.3). Rotating disk resembles in some extent a pump impeller and seems to be particularly well suited to model cavitation conditions in a hydraulic turbomachine. Cavitation is generated here by circular holes or cylindrical bolts situated in the disk surface. Test specimens are usually inlaid in the disk, downstream of the cavitator. In some cases (Fig.4) test samples are inlaid in the stagnator vanes applied at one or two sides of the disk in order to achieve high relative velocity of the liquid. Braking of the liquid flow results in substantial heat generation and therefore extensive cooling systems are typical components of closed circuit disk facili-

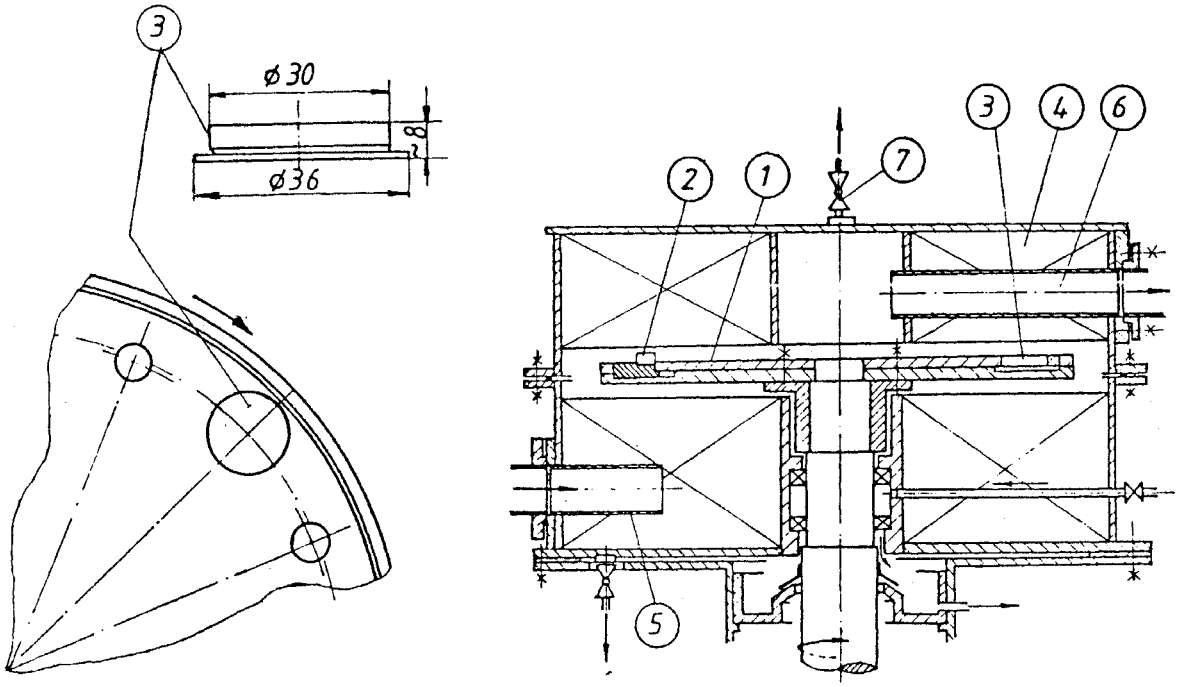

Fig.3 Rotating disk facility in the IMP PAN lab (Gdansk, Poland**): 1 - disk, 2 -cavitator, 3 - specimen, 4 - stagnator vane, 5,6 - working liquid inlet and outlet, respectively, 7 de-areating valve**

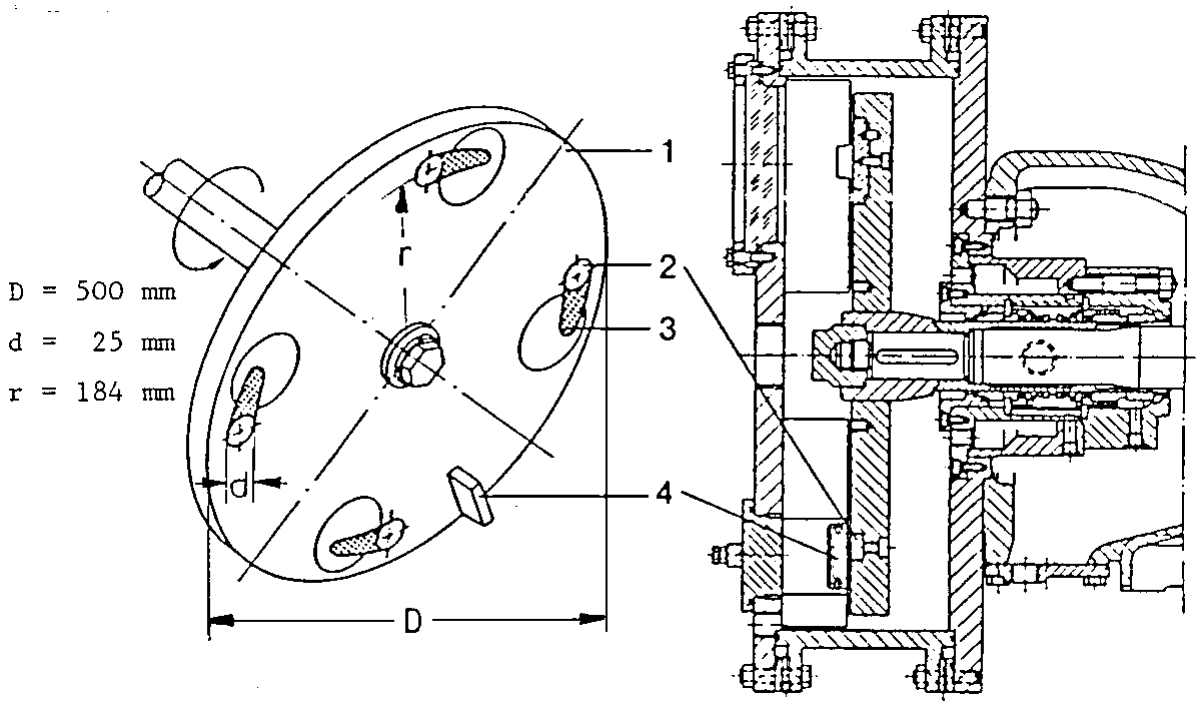

Fig.4 Rotating disk facility in the KSB lab (Frankenthal, Germany**): 1 - rotating disk, 2 - cavitation generating holes, 3 - cavitating wakes, 4 - stationary specimens**

ties. Certain disadvantage of such rigs is a rather long period (5 ÷ 8 min) needed to achieve the steady-state cavitation intensity [7]. The reason is to be seen in design features of the circuit and the change of water quality after putting the rig into operation.

Some changes in water quality in the initial period of operation are also to be expected in vibratory rigs. Cavitation cloud is generated here by a horn vibrating with high frequency

in the liquid. Vibrations are usually generated by a magnetostrictive or piezoelectric transducer. The main disadvantage of the vibratory method is poor reproduction of cavitation conditions in a typical hydraulic machine. The obvious advantages of the method include high erosion rate (test duration of 6 hours is often sufficient), small size of the rig and low energy consumption. By means of dummy samples applied in the initial period of operation it is also easy to ensure steady-state test conditions. Vibratory method was standardised by the ASTM Committee on Wear and Erosion in result of an interlaboratory round-robin test carried out in 1969 [8] on several materials (aluminium alloy 6061-T 6511, austenitic stainless steel Type 316, and commercially pure annealed Nickel 270[1]) described later on as reference ones. The standard developed (ASTM G-32 Standard on Vibratory Cavitation Erosion Test [9]) recommends to include one of these materials into all major comparative tests[2]. The ASTM standard has been taken also as a basis for national standards developed in Poland and Czechoslovakia [10,11]. Some basic requirements following the ASTM G-32 revision of 1998 are shown in Fig.5.

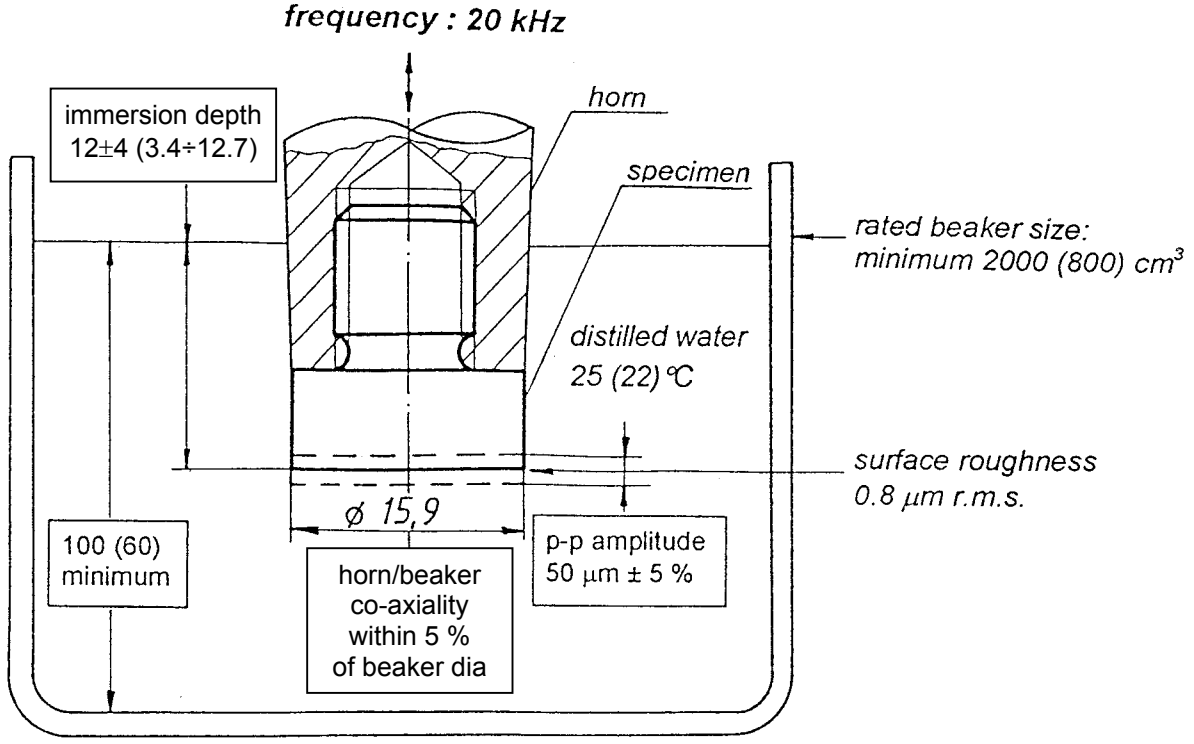

Fig.5 Vibratory rig - basic requirements following the ASTM G-32 revision of 1998. Requirements following the standard version of 1985 are given in brackets.

It was only in 1995 that the ASTM G2 Committee finally concluded its work on standardisation of another test rig. This time the procedure concerned the so-called Lichtarowicz cell (Fig.6) - a cavitating jet device developed by Dr A.Lichtarowicz of the University of Nottingham [12]. Cavitation is generated here in a liquid jet flowing with high velocity out of a nozzle of about ∅ 0.408 mm diameter and impinging a test sample of ∅ 12 mm diameter, situated in front of the nozzle [13]. Reference materials recommended by the ASTM for cali-

[1] Designation after [3].

[2] Following the revision draft of 1990, each major erosion test programme should include the annealed wrought Nickel 200 (UNS N02200, ASTM B160). This material should be also used to check for the rig conformity with the standard. Additional materials to be applied for the needs of comparative tests include soft Aluminium Alloy 6061-T6 (UNS A96061, ASTM B211) and the annealed austenitic steel Type 316 (UNS 31600, ASTM 276).

bration purposes include soft aluminium 1100 (UNS A91100, ASTM B211), wrought Nickel 200 (UNS N02200, ASTM B160) and austenitic stainless steel Type 316 (UNS 31600, ASTM 276). Lichtarowicz cell is characterised by substantial erosion rate, small size and low power consumption. Precise manufacture of all components is of essential significance. Due to their operational advantages, cavitating jet facilities are finding widespread application now.

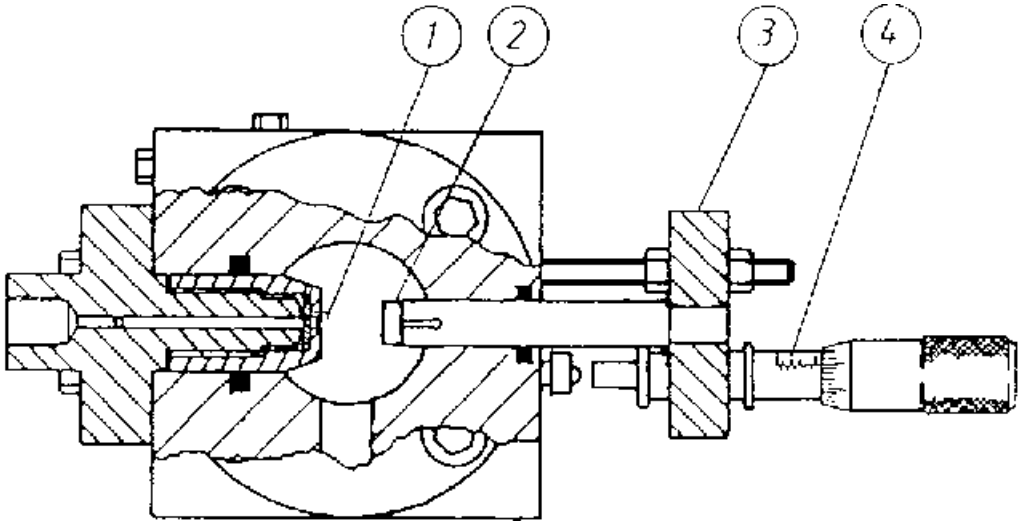

Fig.6 Lichtarowicz cell: 1 - nozzle ∅ 0.4, 2 - specimen ∅ 12.0, 3 - specimen holder, 4 - micrometer head

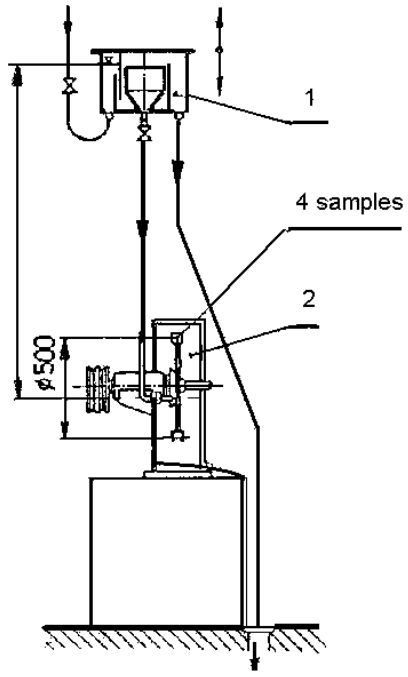

Fig.7 Liquid impact device in SIGMA Research Institute (Olomouc, Czech Republic**): 1 - tank with controlled water level, 2 - test chamber**

From among other devices used to evaluate material resistance to cavitation, liquid jet rigs deserve particular attention. In these facilities a liquid jet strikes periodically a specimen mounted at a rotating wheel rim (Fig.7). Application of liquid jet impact for assessment of material performance under cavitation attack is often considered justified by the assumption that the liquid macrojet impact can model material impingement by a microjet formed in the final stage of cavity collapse. Simple design and operation principle are main advantages of the liquid jet devices. According to the author's knowledge, liquid impact devices were used in the recent past in the laboratories of SIGMA Research Institute (Olomouc, Czech Republic), J.M.Voith GmbH (Heidenheim, Germany) and TURBOINSTITUT (Ljubljana, Slovenia).

It is to be stressed that the difficulties in assessment of cavitation erosion resistance of materials result both from various experimental techniques applied and from the lack of univocality in interpretation of results. In order to enable quantitative evaluations and classification of materials various single-number parameters are applied. Some of them - like volume loss ΔV and mass loss Δm, *mean* and *maximum depth* of erosion *penetration MDP* - are determined after specified test duration, other ones - like *instantaneous erosion rate IER* = $\mathrm{d}(\Delta V)/\mathrm{d}t$ and *mean depth* of erosion *penetration rate MDPR*, incubation period and time needed to achieve maximum

damage rate - usually characterise a specific period of erosion progress. Some general features of the erosion progress are reproduced by the maximum value of the *cumulative erosion rate CER* = ΔV/t and the material durability parameter δ_{cav} as proposed in 1979 by K.Steller [7]. The general disadvantage of single-number parameters is a one-sided assessment of material resistance to cavitation. Therefore, most standards on cavitation erosion tests recommend to make such assessments by comparing whole erosion curves while giving no hints on quantitative analysis of test results

Irrespective of the data processing technique applied, unequivocality and repeatability of erosion test results are surely essential conditions of reliable assessment of material resistance to cavitation attack. Therefore, efforts *to standardise* existing *erosion test methods* deserve priority they are usually attributed to. However, the following aspects of the problem should be borne in mind:

1. The most reliable erosion prediction can be expected if the differences between cavitation loads under lab and field conditions concern rather the total number of cavitation pulses per time and surface area unit than the structure of their amplitude distribution and the damage mechanism. Therefore, standardisation of various test methods and their recommendation for various field configurations seems to be more desirable than attempts to introduce a single "universal" method.
2. While flow rigs (cavitation tunnels and rotating disks) are generally considered to provide cavitation load conditions well resembling those in hydraulic machines and devices, standardisation of these facilities may appear very difficult in practice. In fact, flow rigs are usually pretty expensive devices, often a long period of time in service and considered a significant achievement of local research groups. Furthermore, test methods applied are acknowledged by industrial partners who have already used the results obtained to take technological decisions.
3. As it can be seen from this report, even if all the basic cavitation erosion test methods are standardised, the problem of unsatisfactory compatibility between relative material performance under lab and field conditions will remain unsolved.

An increase of reliability of cavitation resistance assessments can be also striven for by development of techniques enabling to transfer test results from one rig to another and then onto a full-scale hydraulic machine or structure. The most straightforward technique is to test typical representatives of various material groups in order *to establish correlations between their erosion courses* and to apply these correlations to other materials of the same group.

In case of test rigs of the same or similar design one can try to transfer test results using the so called erosion scaling laws [1]. In this respect, validation or *determination of relationships between erosion curves and test parameters* is of essential significance[1].

The R&D activity in all the above outlined directions requires substantial amount of experimental data from test rigs of various design and operating parameters. In order to give access to such a material to all labs interested, the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences (IMP PAN) has put forward an initiative of an International Cavitation Erosion Test (ICET) with the aims formulated as follows:

[1] Another approach possible is to correlate erosion curves with distribution of cavitation pulses divided into fractions of uniform amplitude and to use the method of superposition in order to conclude on the erosion curves corresponding to given cavitation load [8]. A proposal of introducing such a technique into the laboratory practice will be put forward by the Co-ordinator during the ICET Seminar.

- compilation of data on design and operation of existing test rigs,
- comparison and correlation of the damage course and cavitation resistance assessments of selected groups of materials tested under different cavitation conditions,
- establishment of relationships between the damage course and the parameters defining cavitation load conditions,
- creation of the basis for further standardisation of the methods used to assess material resistance to cavitation damage.

Table 1 List of materials subjected to erosion tests within the International Cavitation Erosion Test Programme

general description	*commercial name*
aluminium alloy	PA2[1]
brass	M63[1]
Armco iron	E04[1]
carbon steel	45[1]
acid resistant steel	1H18N9T[1]
polyamide 6 plastics	tarnamide

The ICET programme, proposed to the Potential Participants, has covered tests on 6 materials listed in Table 1. Test materials have been selected in a way providing evident differentiation between their erosion curves - it can be easily noticed that two of them (E04 Armco iron and PA2 aluminium alloy) are typical reference materials used in numerous erosion tests while the next three ones (45 carbon steel, 1H18N9T stainless steel, and M63 brass) are structural materials commonly applied in engineering practice. All the metallic materials were acquired at the CENTROSTAL Steel Storehouse, the main distributor of metals in Poland while the polyamide 6 plastics was obtained from the CHEMIPLAST EVG in Gliwice. Chemical composition, heat treatment conditions and values of some mechanical parameters of metallic materials are to be found in Tables 2, 3 and 4 while the main parameters of polyamide 6 plastics are given in Table 5.

Table 2 Chemical composition of metallic test materials[2]

Chemical component	*Material*				
	E04	45	1H18N9T	M63	PA2
C	0.035	0.43	0.4	–	–
Mn	0.10	0.63	1.37	–	–
Si	0.01	0.26	0.55	–	–
P	0.026	0.030	0.030	–	–
S	0.035	0.033	0.010	–	–
Cr	–	–	17.6	–	–
Ni	–	–	9.40	–	–
Fe	*rest*	*rest*	*rest*	–	–
Cu	–	–	–	*Rest*	–
Al	–	–	–	–	*rest*
others	–	–	Ti:0.60	Zn:32.6	Mg:2.7

[1] Designation according to Polish Standards

[2] Chemical analysis has been conducted at the Institute of Structural Materials and Welding of the Technical University of Gdańsk, Poland.

Table 3 Heat treatment conditions of metallic test materials

material	*technology*	*treatment conditions*		
		temperature	*duration*	*cooler*
PA2	recrystallization annealing	250 °C	30 min	*air*
M63	recrystallization annealing	550 °C	30 min	*air*
E04	recrystallization annealing	600 °C	20 min	*air*
45	heat refining	850 °C	20 min	*air*
1H18N9T	hyperquenching	1050 °C	15 min	*water*

Table 4 Mechanical properties of the metallic test materials[1]

mechanical property	*material*				
	E04	45	1H18N9T	M63	PA2
density[2], kg/m^3	7853	7868	7886	8430	2693
hardness[3], HV_{10}	108.4	192.8	191.0	80.9	71.7
tensile strength, MPa	328	721	605	352	208
yield point, MPa	263	419	225	117	169
modulus of elasticity, GPa	210	210	200	99	70
ultimate strain[4], %	40.5	22	52	65	17
cross section reduction at fraction, %	72.5	39	64	72	63

Table 5 Main physical parameters of the polyamide 6 plastics

density, kg/m^3	1162
relative viscosity of the solution, %	5
relative viscosity of the monomer, %	5
hardness, kG/cm^2	1500
Vicat softening temperature, °C	205

[1] Measured in the Institute of Structural Materials and Welding of the Technical University of Gdańsk, Poland

[2] Measured in the SIGMA Research Institute, Olomouc, Czech Republic

[3] 10 kG load

[4] According to Polish Standards, the ultimate strain A_5 [%] is defined as the maximum relative elongation of a cylindrical rod of diameter D and $L = 5D$ length during a tensile strength test.

Test Participants have been asked to conduct erosion tests on at least 2 specimens of each kind under specified steady state conditions. As usual, it was recommended to continue the tests as long as needed in order to attain the steady-state damage period. It was assumed that the data submitted on the Measurement Cards would comprise main operating parameters of the facility as well as tables of mass/volume losses in course of the test, final values of the mean and maximum depth of pits, data on microhardness distribution, photographs of damaged surfaces and their metallographic structure.

Results are presented in this report and in the *EROSION* database available both on distribution diskettes and through the Internet world-wide web. It is assumed that this report will form a basis for discussion during the ICET Seminar to be held in 1999. The main conclusions following from the results will be summarised in the Final Report to be issued in the year 2000.

In order to specify properly the Test Programme and to make the best use possible of the results obtained a Test Panel has been established. The Panel consists of 6 members listed in Table 6. The data on Test Participants and their test rigs are given in the next section.

Table 6 List of Test Panel members

No.	*Name*	*Affiliation*	*Remarks*
1.	Dr Bolesław G. Gireń	Institute of Fluid-Flow Machinery of the Polish Academy of Sciences, Gdańsk, *Poland*	*Secretary*
2.	Dr Tadeusz Krzysztofowicz	Technical University of Gdańsk, Gdańsk, *Poland*	*Local Advisor*
3.	Dr Andrzej Lichtarowicz	University of Nottingham, *U.K.*	*International Advisor*
4.	Prof. Hartmut Louis	University of Hannover, *Germany*	*International Advisor*
5.	Prof. Marian Mazurkiewicz	University of Missouri, Rolla, *U.S.A.*	*International Advisor*
6.	Dr Janusz Steller	Institute of Fluid-Flow Machinery of the Polish Academy of Sciences, Gdańsk, *Poland*	*Test Co-ordinator*