THE RESULTS OF CRUDE REFINING EQUIPMENT DIAGNOSTICS AND THEIR ANALYSIS

A.M. Kuznetsov, S.P. Bykov, M.A. Khramenok

Open joint stock company "Irkutsk Scientific Research and Designing Institute of Chemical and Petrochemical Engineering"

Irkutsk
Russia

NDT of the equipment being in service provides the information about its actual condition and is one of the core elements of the technical diagnostics contributing an important phase in industrial safety at the chemical, petrochemical and crude refining enterprises.

The accumulation of unique data regarding the characteristics of technical units under continuous service results from technical diagnostics which, in its turn, provides the possibility to elaborate new approaches for design requirements, material selection, manufacturing, conditions and terms of defect-free performance of potentially hazardous equipment.

Analysis of equipment condition based on the technical diagnostics results enables to develop the approaches for rejection statistics within the theory of reliability, to detect the mechanisms and objective laws for defect formation, to enlarge the ideas about material properties, advantages and drawbacks of structural solutions.

By appointing the inspection amounts and methods for an item that has completed its service life it is necessary to correctly indicate those components and elements that are under the most stressed conditions or that are subjected to corrosion or erosion.

To reach such a goal it is necessary to define the type of an imperfection (structural or technological, etc) that could occur and develop during the specific period of operation taking into account reliability of the elements [1] and the types of inspection methods that could be the most effective for the indication detection.

With the petrochemical enterprise, during the long-term service the bearing elements of construction are subjected to mechanical, thermal and corrosion impacts that could lead to indication formation, corrosion damage, material mechanical property changes etc.

According to the common element reliability model [1] for equipment (machinery) operating under dynamic conditions there are three periods of item functioning:

- breaking in when structural, technological and production defects are detected;
- normal operating condition that is characteristic of sudden failure of continuous intensity;
- ageing when rejection intensity grows.

During the first period of operation not found imperfections are the concentrators of stresses which lead to cutback of safety factor. Short period of running-in failures demonstration and their higher intensity as compared with sudden failures provided that probability of load occurrence sufficient for fraud item destruction is higher then probability of high load occurrence and, correspondingly, sudden failure associated with it.

Rejection distribution law during this period is defined by distribution of production defects after acceptance control has been passed. This law reflects rejection intensity decrease to a constant value during a comparatively brief period.

The law of critical load occurrence probability distribution is specific for the second period and could be described by the extreme value models [2]. With the sudden rejection occurrence probability distribution, the exponential distribution is used. This is the simplest model defined by the only parameter that is specific for rejection intensity or mean time to failure.

Rejections at the stage of ageing are due to the natural thermodynamic processes of destruction of an item under loading and interaction with the media. The most adequate models for rejections resulted from wear are the models based upon normal, logarithmically normal and Weighbull laws that are dependent on the element "age" and specific for increasing of the rejection intensity through time.

It's possible to use the above method also for equipment analysis that operates under quasi static perturbations based on the large time intervals (long-term exploitation).

We have implemented a defect analysis of the equipment at one of the Russian refineries; imperfections were detected with flaw detection held by a non-destructive crew during a year. There were 103 units to be inspected, mainly reactive equipment as well as column and capacitive equipment. The traditional refinery units were also inspected: hydro cracking, electrostatic desalting of oil, vacuum distillation of fuel oil etc. About 25% of all units meant to be used in highly corrosive media and were made of austenite steel X18HT10T either with protective layer made of such steel used as cladding or cladding made of steel 08X13. Figures 1 – 3 show the main results of investigation. The obtained results enable to subdivide all the inspected apparatuses onto two groups according to their technological use and detected imperfections were divided into defects occurred while manufacturing and the operational ones occurred during the operating period.

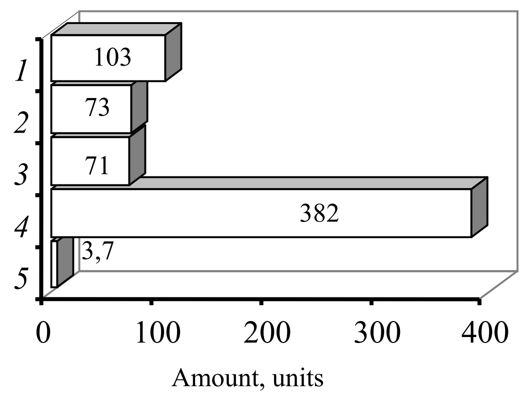


Fig. 1 The main results of investigation of refinery equipment

1 – total amount of apparatuses; *2* – amount of apparatuses having defects; *3* – amount of apparatuses having defects in percentage of all the apparatuses; *4* – amount of defects detected; *5* – amount of defects per apparatus

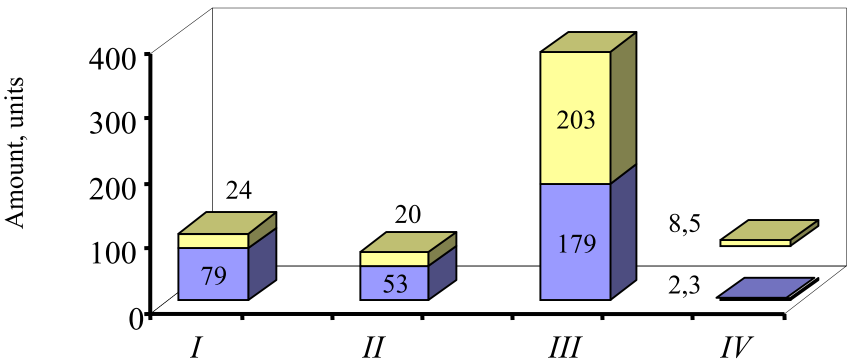


Fig. 2 Total distribution of defects per apparatuses

I - total amount of apparatuses; *II* - amount of apparatuses having defects; *III* – total amount of defects; *IV* – amount of defects per apparatus

■ - apparatuses without corrosion protection; ■ – apparatuses with corrosion protection

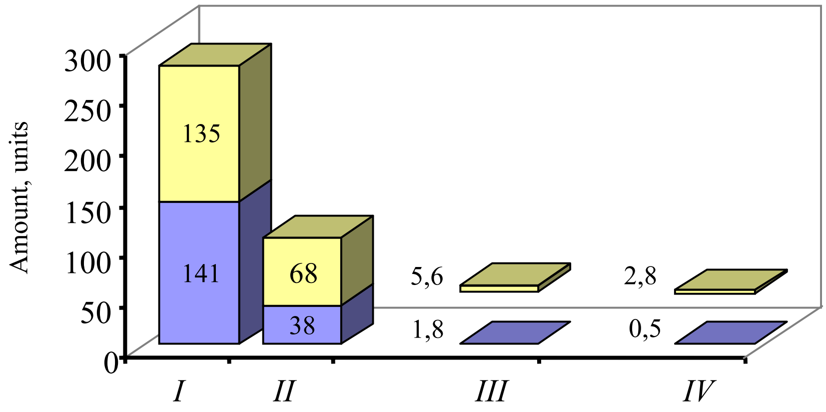


Fig. 3 Defects distribution according to groups

I – manufacturing flaw; *II* – operational defects; *III* – amount of manufacturing flaws per one apparatus; *IV* – amount of operational defects per one apparatus

■ - apparatuses without corrosion protection; ■ – apparatuses with corrosion protection

The main damaging factors that lead to occurrence of defects affect, as a rule, the internal equipment surface. In this regard the most expected defects are surface defects; therefore all apparatuses were internally and externally inspected as well as magnetic particle and dye penetration tested to the extent of 25% of welds from the internal side. During the inspection the areas having maximum stresses and intersection points, longitudinal and circumferential welds were chosen; in specific cases an ultrasound analysis was used. Selection of inspection areas (according to program) has its own peculiarity but taking into consideration that inspection was held on units having limited access and therefore the actual selection was influenced by a range of circumstantial factors it could best be considered that the units were selectively inspected using casual principle in amount of 25% of total length of bearing elements.

Decision making about an amount of inspection in percentage of total amount of elements couldn't be done without notice of three factors: actual impurity of apparatus D, total amount of elements in apparatus N and bias value σ_p [3].

$$\frac{n}{N} = \frac{D(1-D)}{\sigma_p^2(N-1) + D(1-D)}, \qquad (1)$$

where n is a sampling value.

If rated error and total amount of elements having increased actual defect contamination (at least up to $D = 0{,}5$) are present then the amount of control in percentage shall be increased. On the other hand, if the same amount of contamination and ordered standard error are present during the increase of N the amount of sampling n shall grow but not proportionally with N. Virtually D might be substituted for its evaluation p.

To complete the task of actual contamination of an item with defects D it could be solved using a confidence limit detection having an ordered confidence probability α that overlaps the estimated parameter D. The confidence limit width is estimated by a condition [4]:

$$W\{|p - D| \le \varepsilon\} = \alpha , \qquad (2)$$

in which ε is the half of an interval and probability W is defined by the law of estimation distribution p.

To make it even simpler one could assume that the estimation of p is normally distributed (actually, its distribution is hyper geometrical). Maximum deviation from a true quantity of defects D (if the range of confident probability is (1-α)) is evaluated as a product of $t_\alpha \sigma_p$, where t_α is a confident factor or a rated deviation [2]. Under such circumstances the biggest numerical value of an unknown parameter D is equal to:

$$D_в = p + t_\alpha \sigma_p \tag{3}$$

By analogy but using a minus-sign one could record an expression for the minimum numerical value D_H and, matching the value σ_H in the obtained expressions the system of two these formulas could be solved with two undetermined values:

$$D_H, D_в = \frac{1}{n + t_\alpha}\left\{ d + \frac{t_\alpha^2}{2} \mp t_\alpha \sqrt{\frac{d(n-d)}{n} + \frac{t_\alpha^2}{4}} \right\} \tag{4}$$

where d is an amount of defects.

The obtained interval is asymmetric to p and the more this asymmetry is, the closer is D to 0 or 1. This expression could be used while distributing other evaluations of D (for instance, hyper geometrical, binominal or Poisson's) because it was obtained from the general considerations.

To practically evaluate the value of contamination of an apparatus with defects D one could find its dependence on values d, n, N. Then do the system of formulas consisting of expressions (1), (3), (4). As a result of such transfigurations obtain:

$$D = \frac{2D_в + k + \sqrt{(2D_в + k)^2 - 4(1+k)D_в^2}}{2(1+k)}, \tag{5}$$

where the coefficient $k = \sqrt{\frac{1}{n}\left(\frac{N-n}{N-1}\right)}$.

Using the formulas (4) and (5) the nomograms shall be built for contamination with defects D for the required ranges of N, n and d. Contamination of an apparatus with defects shall be evaluated using these ranges as well as its confident interval ordering a sampling value and an amount of defects found for it. For example, with the investigation made for an apparatus there were 15 defects found with the total amount of estimated elements $n = 40$. (fig.4).
D = 46% could be found from this chart.

Since the investigated equipment had been operating not less than for 20 years its had already passed the stage of breaking-in long ago and therefore is either under normal operating conditions or ageing. It should be noted that this kind of equipment generally possesses two types of defects: technological or manufacturing defects and operating ones that formed during operation. Presence of manufacturing defects is considered in conjunction with the fact that they indicated themselves at the stage of breaking-in but weren't a source of fatigue imperfections development and, in the long run, didn't affect the item working efficiency. Cracks and corrosion pits shall logically be relevant to operational defects and all the others are relevant to manufacturing defects. It possible to consider that the cracks occurring during the manufacture were repaired through the years of operation and such defects as pores, cuts, lack of penetration etc., either corresponded to the norms at the moment of manufacture or weren't identified at the acceptance control.

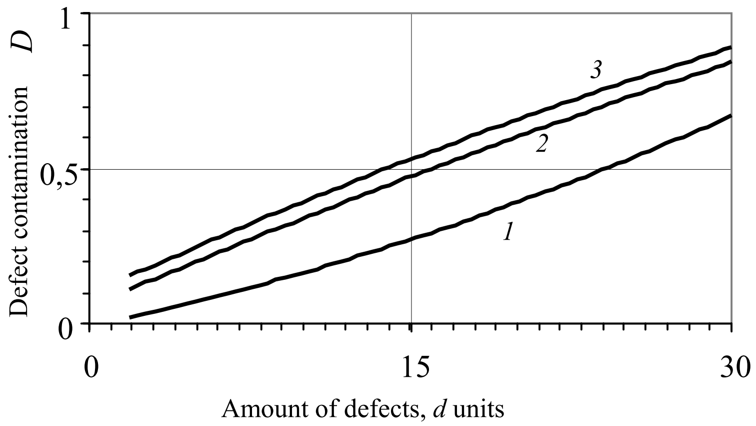


Fig. 4 Nomogram for identification of contamination *D* of an apparatus with defects depending on the amount of identified defects *d*

1 – lower boundary of contamination *D* values of an apparatus (confident interval 52%); *2* – actual contamination *D* value of an apparatus for an amount of sampling for a sampling amount $n = 40$ having $N = 100$; *3* – upper boundary of contamination *D* values of an apparatus (confident interval 28%)

The data analysis shows that the ranges of defectiveness for apparatuses without corrosion resistance and for ones having it in form of cladding layer made of steel 08X13 or X18H10T are different.

Provided that the total range of defectiveness is 3,7 defects per apparatus then it is 8,5 for the apparatuses having such resistance; that means more than 3,5 times of the apparatus defectiveness without corrosion resistance. Range on the operational defects is more than 5 times higher which is possibly explained by the work of such apparatuses (having corrosion resistance) in rougher conditions (media, temperature etc) and on the manufacture defects – three times higher which, in its turn, shows malfunction during manufacture and/or repair that had been performed the previous years.

Especially large amount of defects was identified in apparatuses with cladding material made of steel 08X13 (more than 70%). Besides, among the operational defects to the equal extent there are cracks and corrosion pits.

Corrosion pits weren't indicated in steel X18H10T whereas all operational defects are cracks; their quantity approximately equals to quantity of manufacture defects found in these apparatuses. The total amount of defects in above steel is 28% of all defects found in apparatuses operating in corrosion media.

Apparatuses having no corrosion resistance are considerably less defective including either manufacture defects or operational ones. Manufacture defects – pores, cuts, lack of penetration etc are uniformly distributed along the apparatuses regardless of the material they are made of. Operational defects – cracks and corrosion pits are localized in apparatuses made of steel Vst3kp, Vst3sp.

Figures 5 – 8 show the results of analysis held to distribute the defect types (defects of manufacture and operational defects) according to apparatuses investigated (with or without corrosion resistance), the material they are made of, and according to the areas at which the defects were identified (parent material and weld joints).

Distribution of an average amount of manufacture and operational defects along the apparatuses depending on the material (fig.5) shows that the apparatuses made of materials without austenite have a rather uniform distribution of manufacture defects with an average amount about two per unit of equipment (higher indication has steel 20K). Just the same situation is for the operational defects in these steels. In apparatuses made of steel Vst2sp and 20K the operational defects weren't found.

For the apparatuses operating in high corrosion media the situation is a bit different. The most defects were found in apparatuses made of steel 16GS and Vst3sp with cladding material made of steel 08X13 as well as in apparatuses made of X18H10T. It has to be admitted that in above apparatuses the high average amount of defects is observed, either manufacture or operational defects.

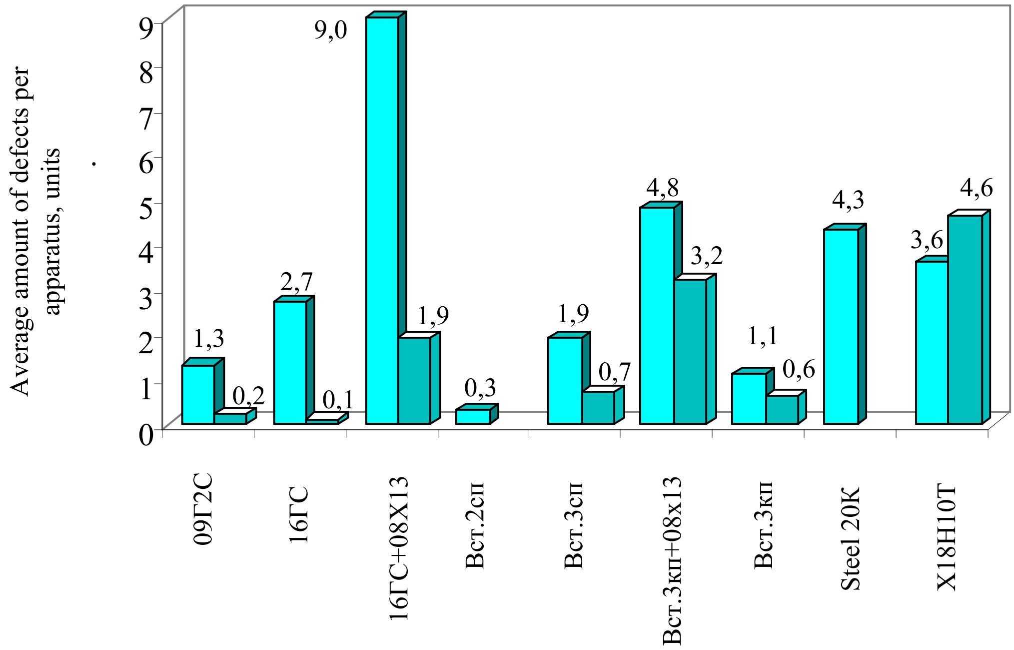


Fig. 5 Average amount of manufacture and operational defects in apparatuses depending on their material

- manufacture defects; - operational defects

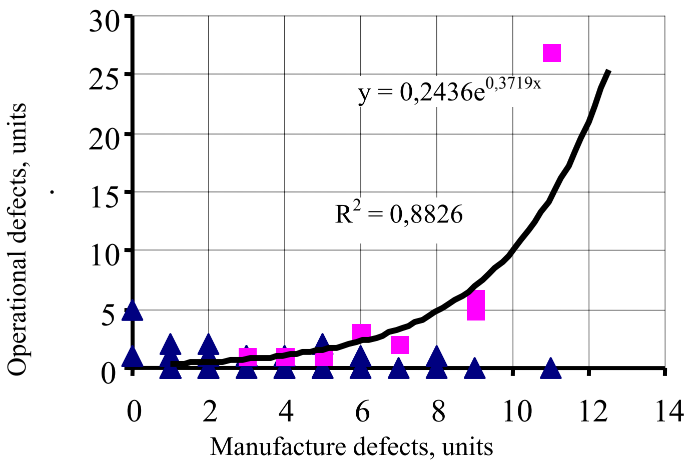


Fig. 6 Relation between amount of manufacture and operational defects

- apparatuses with corrosion resistance; - apparatuses without corrosion resistance

The data analysis about an amount of manufacture and operational defects along all the inspected apparatuses (fig.6) shows that apparatuses without rust protection don’t have any dependence between these two values but in apparatuses that have rust protection there is an exponential connection between amount of manufacture and operational defects:

$$d_{экс} = \left(0,24 * \exp\left(0,37 * d_{изг}\right)\right), \qquad (6)$$

where is $d_{экс}$ an amount of operational defects; $d_{изг}$ is an amount of manufacture defects; approximation reliability of the data obtained by an exponent R^2 =0,88

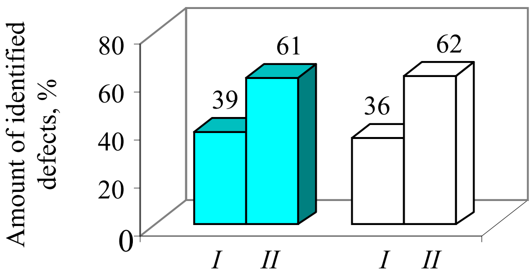


Fig.7 Distribution of detectability according to control methods

I – amount of identified defects, in %;
II – percentage of defects identified by DP;

– manufacture of defects;

☐ – operational defects

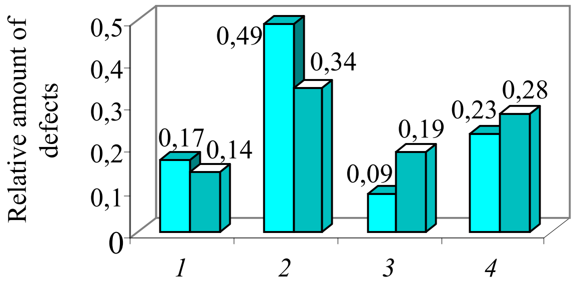


Fig. 8 Distribution of detectability according to control zones

1 – longitudinal welds; 2 – circumferential welds; 3 – parent material; 4 – fillet weld;

– manufacture of defects;

– operational defects

The analysis gives an evaluation of contamination of apparatuses with defects in terms of possibilities of the applied inspection methods and the amount of control that has been appointed according to the program. These very two factors identify reliability of the evaluations concluded. Figure 7 gives the distribution of manufacture and operational defects identified by the methods: dye penetration (DP) and visual (VI) inspections. For both types of defects 40% are identified by VI and 60% by DP. This indicates at high efficiency of visual control and necessity of its application using instrument matching.

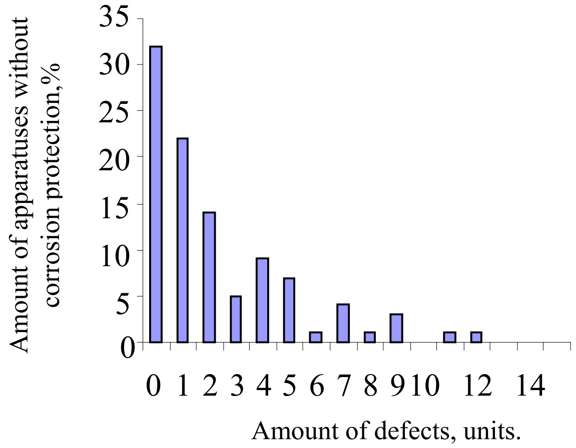
With the appointing of amounts and methods of inspection it is necessary to correctly designate the item elements subjected to the highest stressed state or corrosion and erosion. Figure 8 shows the distribution of manufacture and operational defects related to overall amount of defects of corresponding type and according to the main elements of inspected equipment. The diagram analysis shows that character of distribution along the main elements keeps the same for manufacture and operational defects. The difference is in remarkably greater amount (two times as much as for operational defects) of manufacture defects in a parent material and that's obvious because the parent material surface is subjected to damaging factors as well as the other apparatus elements. Defect amount two-times excess of both types in circumferential welds could be explained by a 100% inspection of circumferential and longitudinal weld crosses. Besides, the inspected dimension of a circumferential weld is twice as much as longitudinal. Fillet welds have approximately 25% of all the defects. On the one hand, it could be explained by a greater amount of penetration lacks from the internal side of an apparatus while welding of nozzles (formerly accepted by norms) which can be considered as the sources for operational defect formations (corrosion pits, cracking); on the other hand, nozzle area welds are in the highest stressed state (SS) as compared with circumferential and longitudinal welds [5]. Besides, fillet welds were 100% inspected.

It has to be admitted that apparatuses without corrosion resistance are in the normal operating conditions when sudden rejections (occurrence of operational defects) are the Poisson's flow in time having constant intensity λ that don't depend on manufacture defects. This results from Poisson's approximation of distribution along apparatuses that is presented in figure 9.

In this respect there is a question about the necessity of operational defect identification in such apparatuses while investigating and repairing. In the groups of investigated apparatuses the amount of manufacture defects is 79% of the identified defects – this means 141 defects; any of them obtained a technical solution upon repair, sampling was implemented and backing-up weld was made as well as repeated inspection.

Alternate way is about apparatuses operating in corrosion environment; rejection intensity in such apparatuses is considerably higher and there is a relation between these rejections and an amount of manufacture defects. Using these results one could suppose that the apparatuses either reached their period of ageing or operate in abnormal conditions due to malfunctioning during manufacture (repair), incorrect material selection for the given technique or due to simultaneous actions of these two factors. The analysis of distribution of defects along these types of apparatuses (fig.9,b) points out at presence of a big share of apparatuses having a considerable amount of defects (occurrence of additional maximums) that in the long run gives evidence about malfunction of apparatuses of this kind related either with technological regression or low quality repair.

a



б

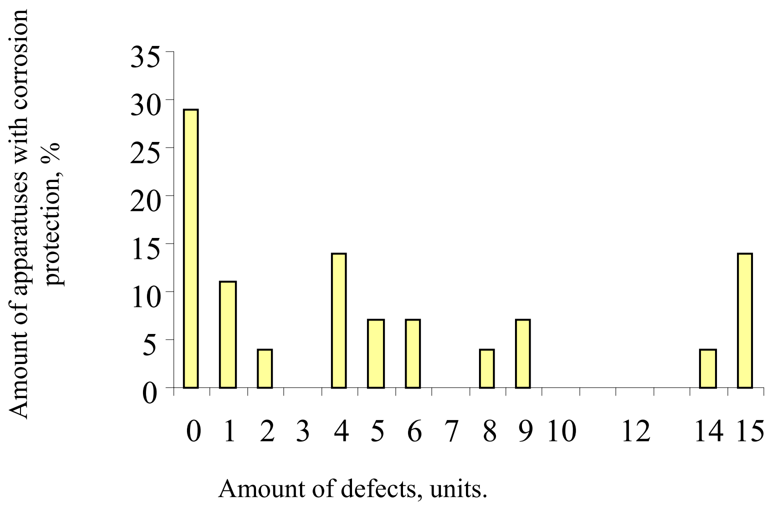


Fig. 9 Distribution of imperfections according to the types of apparatuses and their elements

a – distribution of all identified defects on apparatuses without armoring;

b – distribution of all identified defects on apparatuses with armoring.

Figure 10 shows distribution of operational defects (cracks and corrosion pits) identified by DP and VI methods for the apparatuses operating in high corrosion media. For these apparatuses the vast majority of manufacture defects are met in weld joints. In apparatuses made of steel 08X13 the main damages are due to corrosion process. In apparatuses made of steel Vst3sp with cladding material made of 08X13 and in apparatuses of steel X18H10T the most specific defects are weld cracks, besides, specific operational damages for it are fillet weld cracks (65% of defects in apparatuses made of steel X18H10T). This could be explained by the fact that actual calculation methods for non-detachable joint of high pressure vessels don't take into account the type of stress-deformed state of the metal in the highest concentration stress zones (nozzle areas) under real conditions of thermo-cyclic loading [5].

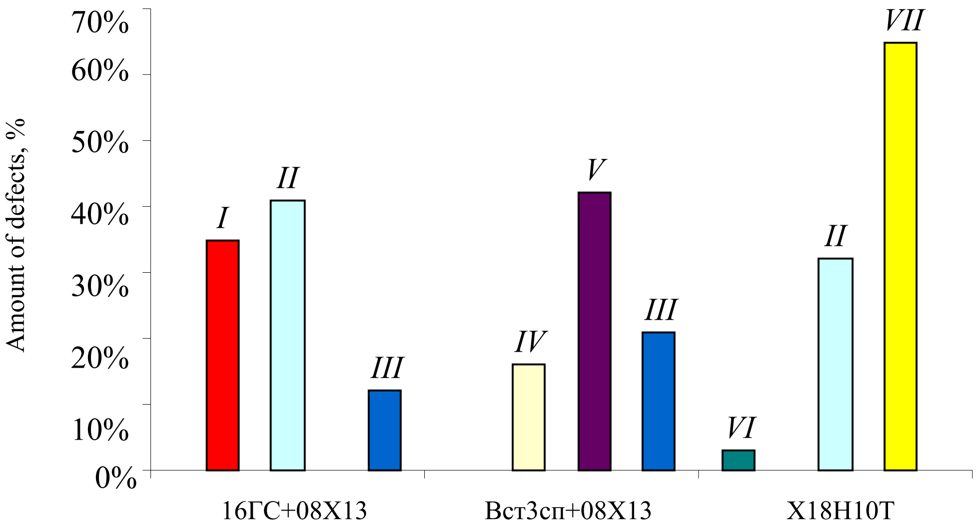


Fig. 10 Distribution of operational defects along apparatus elements operating in high corrosion media
I – longitudinal weld cracks; *II* – circumferential weld cracks; *III* – corrosion damage of fillet welds; *IV* – corrosion damage of longitudinal welds; *V* – corrosion damage of circumferential welds; *VI* – parent metal corrosion damage; *VII* – fillet weld cracks

According to above investigations the following conclusions shall be made:

1. Sampling of apparatuses being analyzed for the correct statistical analysis shall be subdivided into sub collections or according to approximation of technological conditions or according to structural and material specifications.
2. Approach to the norms of apparatus quality evaluation regarding the apparatuses that have already reached deadline but still operate under normal operation conditions can be corrected to its relief but as for the apparatuses that have increased intensity of defect formation and relation between manufacture and operational defects the norms shall be strengthened.
3. The results of selective NDT enable with the specified degree of accuracy depending on the sampling amount to evaluate the true contamination of a unit with defects (fig.1). The extent of an error may be used to calculate the residual life and appointment of a further safety operation date.

Bibliography:

1. **Bazovsky I.** Reliability. Theory and practice. – M.: Mir, 1965. – 324 pp.
2. **Gumbel E.** Statistics for extreme values. – M.: Mir, 1965.-373 pp.
3. **Gnedenko B.V., Belyaev Y.K., Solovyev A.D.** Mathematical methods in reliability theory. – M.: Nauka, 1965.-524 pp.
4. **Schwarz G.** Selective method. – M.: Statistika, 1978.-211 pp.
5. **Tsvick L.B., Khramenok M.A., Shapova M.V.** Opening reinforcement in pressure vessel nozzle areas and their impact on their stressed condition // Izvestiya VUZov. Mashinostroyenie. – 2008.-№1. – Pp. 18 – 24.