THE RISK OF HYDROGEN EXPLOSION IN A SUBMARINE P. IV
THE IMPLEMENTATION OF HIGH RISK PROJECTS

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ABSTRACT

This series of articles on high risk projects looks at the example of the modernisation of hydrogen incinerators on a submarine. The article describes problems connected with the management of such a project.
Keywords: project risk, project risk analysis, risk analysis methods.

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INTRODUCTION

A project, described in the previous articles of this series connected with the modernisation of hydrogen incinerators on a submarine, was considered a high-risk project. Technical problems have been discussed in earlier articles of the series. This, the last of them, will demonstrate the management problems encountered.

To understand the scale of the problem encountered during the replacement of the catalyst inserts, it is necessary to taking into account the following:

- potential obstacles in relation to supplies from Russia,
- an extremely short project implementation time, which prevented the carrying out of appropriate levels of research,
- a lot of pressure since the project constituted a small element in the scope of the overhaul of the submarine, which however could not be omitted,
- low project budget,
- The $Academy's$ competences in solving catalysis-related problems in catalysis were not very high,
- The $Academy$ lacks suitable traditions and thus proper facilities to conduct works of this type.

INTRODUCTION

The explosion protection system provided on a submarine (OP), which by the nature of its purpose works separately, constitutes a key problem situation from the point of view of crew safety and combat mission security.

One of the factors that creates a potential fire and explosion hazard is the presence of hydrogen, which can be emitted continuously, however its greatest intensity is noted during the charging of an integral battery pack [1].

Tab. 1

The generated Strengths, Weaknesses, Opportunities and Threats (SWOT), with regard to internal and external conditions, are all linked to the assurance of the required quality of the hydrogen burning process.

S	1	available scientific-research base
	2	available scientific-research potential
	3	experience gained
W	1	insufficient military repair base
	2	old burner blocks
	3	old burner block installations
O	1	NATO accession
	2	access to the latest technologies
	3	modernisation plan of the Armed Forces
T	1	inoperability of the submarine
	2	fire hazard on a submarine
	3	lack of spare parts
S (Strengths): all that constitutes an asset or advantage of the system analysed		
W (Weaknesses): all that constitutes a weakness, barrier, fault of the system analysed		
O (Opportunities): all that creates an opportunity for a positive modification of the system analysed		
T (Threats): all that creates a threat of an unfavourable alteration in the system analysed		

The protection system, which guards against possible threats related to the hydrogen system, consists of various subsystems which also include hydrogen incineration systems. An analysis of the context of ensuring the required quality of the process of hydrogen combustion was carried out with the use of the $SWOT$ method [1].

GENERATION PHASE

The results of the generation of the expected strengths, weaknesses, threats and opportunities are collectively presented in tab. 1. Strengths include anything that constitutes an asset or advantage of the analysed system, whereas weaknesses include anything that constitutes a weakness, barrier or fault of the analysed system.

Tab. 2

The results of the analysis of the links between *SWOT* for the internal and external conditions for the assurance of the required quality of hydrogen combustion process.

		O.Opportunities								T.Threats							
		1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.Strengths	1	1	2	2						2	2	2					
	2	0	2	2						2	2	2					
	3	1	2	2						2	2	2					
W.Weaknesses	1	0	2	2						2	2	2					
	2	0	1	2						2	2	2					
	3	0	1	2						2	2	2					

0 no effect
1 weak effect
2 strong effect

Tab. 3

The results of an implication analysis for the strong ties between *SWOT* for the internal and external conditions for the assurance of the required quality of hydrogen combustion process.

		O. Opportunities						T.Threats						O. Opportunities						T.Threats					
		1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
S.Strengths	1		N	**Y**				N	**Y**	N					**Y**	N				N	N	N			
	2		**Y**	**Y**				N	**Y**	**Y**					N	N				N	N	N			
	3		N	**Y**				N	**Y**	**Y**					**Y**	N				N	N	N			
W.Weaknesses	1		N	N				**Y**	N	N					N	**Y**				N	N	N			
	2			N				**Y**	**Y**	N						**Y**				**Y**	**Y**	**Y**			
	3			N				**Y**	**Y**	N						**Y**				**Y**	**Y**	**Y**			

– Does a given strength allow to use a particular opportunity?
– Does a given strength allow to eliminate a particular threat?
– Does a given weakness limit the possibility of using a particular opportunity?
– Does a given weakness raise the risk connected with a particular threat?

– Does a given opportunity enhance a particular strength?
– Does a given opportunity allow to eliminate a particular weakness?
– Does a given threat eliminate a particular strength?
– Does a given threat bring out a particular weakness?

Y–Yes; N–No

Opportunities encompass anything that creates an opportunity for a positive modification of the system analysed. Threats include anything that creates a threat of an unfavourable alteration in the system analysed.

ASSOCIATION ANALYSIS PHASE

The association analysis, in relation to the generated *SWOT* for internal and external conditions, related to project implementation was conducted with the use of a three-grade scale:

- 0 lack of association,
- 1 weak association,
- 2 strong association.

The results of association analysis are shown in tab.2.

The numbering of the generated *SWOT* for internal and external conditions of project implementation are identical for tab.1 and tab.2.

DEDUCTION OF THE OCCURRING IMPLICATIONS

The analysis of implications of the discovered strong associations for the left side of tab.3 was carried out by providing answers to the following questions:

- Does a given strength enable the use of a particular opportunity?
- Does a given strength enable the elimination of a particular threat?
- Does a given weakness limit the possibility of using a particular opportunity?
- Does a given weakness raise the risk connected with a particular threat?

and for the right side of tab.3 the answers to the following questions were provided[2]:

- Does a given opportunity enhance a particular strength?
- Does a given opportunity allow to eliminate a particular weakness?

- Does a given threat eliminate a particular strength?
- Does a given threat bring out a particular weakness?

The results of the implication analysis collected in tab.3, in relation to strong ties, preserve the *SWOT* score applied in tab.1 and tab.2.

ANALYSIS RESULTS

Only strong associations were written off for which deterministic links were revealed[3] in the form of a positive response to questions presented in tab.3. For instance:

Will the available scientific and research base allow us to use the opportunity associated with the modernisation plan for the Armed Forces?

Generally speaking, the scientific and research base should allow the use of the opportunity associated with the *Armed Forces* modernisation plan. At present, the *Academy* lacks permanent stations dedicated to conducting tests on the catalytic efficiency of hydrogen burning systems, however it is in possession of components that make it possible to set up temporary test benches.

Will the available scientific and research potential enable us to take advantage of the opportunity connected with the access to the latest technologies?

It seems that the available possibilities are sufficient to exploit the opportunity of accessing the technologies, which can contribute to the increase in skills, that have an effect on boosting the scientific and research potential of the *Academy*.

However, in relation to issues concerning the research on effective methods of hydrogen burning, it is important to take note of the lack of will to invest in the transfer and development of the said technologies to the Academy's *advantage*.

A further part of the analysis was omitted here as it had been previously described [2]. The conclusion that is drawn from it is contained in the summary of this paper.

CONCLUSIONS

A number of conclusions can be drawn from the conducted context analysis:

- As for now, the open market does not offer good solutions for hydrogen combustion that could replace the existing systems.
- National research led to the development of technology demonstrators that raise hope regarding the quick development of effective systems to replace the existing installations.
- The available laboratory base is not equipped with the necessary dedicated test benches to inspect hydrogen combustion installations, hence during the project implementation it had to be built from the available components.
- The possessed experience gives hope regarding the performance of modernisation on hydrogen combustion systems, although it also entails a certain risk that such activities will not bring the desired effects.

DEFINITION PHASE

The definition phase allowed the definition of a general process map. It defined the basic *C TQ*[4] requirements; critical from the point of view of quality assurance.

TASK

The primary task consisted in the restoring of the efficiency of a catalytic reactor for hydrogen combustion in the system of battery facilities ventilation. Technical parameters defining the system capacity have been described in previous articles of this cycle.

CONTEXT

Hydrogen combustion is part of the anti-explosion / fire protection system on a submarine, where one of the factors producing a potential threat of explosion is hydrogen emitted from an integral battery pack.

JUSTIFICATION

Why is it worth implementing the project?

Due to possible impediments in the delivery of strategic spare parts from Russia, attempts have been made to replace Russian suppliers with domestic deliveries or supplies from the EU countries.

To the *Academy*, this constitutes an opportunity to prove its acquired capabilities[5] in the area of provision of a rapid response to the needs of the *Polish Armed Forces* in the implementation of technological changes in the use of military equipment and armament.

Why is the project of key importance at present?

The project is part of an unresolved problem situation. The ship repair is nearly complete, however due to lack of possibility of obtaining services from the open market, the hydrogen combustion system cannot be handed over to the user.

What are the consequences of a failure to complete the project?

Further inability to perform the modernisation of the hydrogen combustion system with the simultaneous time pressure creates the risk of a failure to complete the contract.

What are the other undertakings related to the project of similar or higher priority?

The project is part of the implemented renovation of a submarine and was adopted as a condition for signing the contract for the performance of the said works.

What are the implications of the project objectives for the mission of the *Polish Armed Forces*?

The implications for the *Polish Armed Force,* and the *Polish Navy,* lieto a large extent in the mental sphere of the command officers as they are at risk of having a vessel returned that does not possess a fully functional hydrogen combustion system, even though it has been contractually provided for as part of the equipment. It should be noted, however, that a significant proportion of submarines do not possess such systems.

Modern batteries do not emit as much hydrogen as their predecessors. Obviously, the provision of a hydrogen combustion system increases the safety and tactical capabilities of a submarine – though not critical in peace, such equipment may prove essential in combat activities.

What are the hazards diagnosed at the stage of conducting the feasibility study for the project?

Preliminary risk analysis related to the implementation of the project was carried out using the *FMEA*[6] method [3]. Risk analysis using the *FMEA* method focuses on the capacity for the early identification of potential risk, and planning of rapid counteraction of the effects of its materialisation in the system or the process occurring therein on the basis of expert knowledge. Initial diagnosis allowed the definition of 8 threats in the considered process related to four types of problems, which are collectively presented in tab.6 below:

- lack of facilities dedicated to works with the use of hydrogen,
- time pressure,
- limited budget,
- lack of market recognition.

OBJECTIVES AND STRUCTURE OF THE PROJECT

Main hypothesis: It is possible to conduct modernisation of the hydrogen incinerators by the *Naval Academ.*

Supporting hypotheses:

1. It is possible to build a monitoring station for the required operational parameters of hydrogen incinerators from the equipment owned by the *Academ.*
2. The *Academy* staff have sufficient skills to build a monitoring station for the basic operational parameters of hydrogen incinerators.
3. It is possible to commission the performance of checks and calibration of the instruments monitoring the composition of hydrogen to an authorised external company.
4. It is possible to safely and dynamically mix hydrogen with air to produce hydrogen-air mixtures needed for catalyst and delivery acceptance tests.
5. The open market offers catalysts for hydrogen combustion which may replace the original ones.
6. It is possible to build test benches to carry out reliable acceptance tests regarding the efficiency of hydrogen incinerators.
7. There is a significant risk of project non-performance and the requirement to pay penalties.

Main objective: modernisation of hydrogen incinerators.

Specific objectives *(PDS)*[7]:

1. Performance of a measurement station ensuring measurements within the required range and reliability level.
2. Performance of a station for the production of hydrogen-air mixes guaranteeing the required composition at the required reliability level.
3. Selection of potential catalyst types.
4. Setting up of a station and conducting catalyst tests.
5. Performance of a station and conducting in-house and acceptance tests on hydrogen incinerators.

Main task: Handing over of operational hydrogen incinerators.

WBS Specific Tasks[8]:

1. Construction of a monitoring station for basic process parameters of catalytic converters and hydrogen incinerator.Analysis possibility to commission a calibration service at least for the measuring devices to ensure safety of working with hydrogen-air mixtures and equipment whose indications will constitute the basis for the acceptance testspossibility to use computer monitoring of the measured parameters
   - 1.2 Station design
   - 1.3 Equipment purchases
   - 1.4 Station performance
   - 1.5 Station calibration and tests
2. Station for the production of hydrogen-air mixtures
   - 2.1 Analysis
     - 2.1.1 safety limits for working with hydrogen-air mixtures
     - 2.1.2 possibility of adjusting the hydrogen flow
     - 2.1.3 possibility of adjusting the air flow
     - 2.1.4 possibility of effective mixing of hydrogen and air flows
     - 2.1.5 possibility of using a station for monitoring the basic process parameters of catalysts and hydrogen incinerators in order to monitor the composition of the obtained hydrogen-air mixture
   - 2.2 Designs
     - 2.2.1 hydrogen dispenser
     - 2.2.2 air flow control
     - 2.2.3 connection of the station monitoring the basic process parameters of catalysts and hydrogen incinerators in order to monitor the composition of the obtained hydrogen-air mixture
     - 2.2.4 a complete station
   - 2.3 Station performance
   - 2.4 Station tests
3. Catalyst test station
   - 3.1 Analysis
     - 3.1.1 finding of hydrogen combustion catalysts
     - 3.1.2 discerning the possibilities of catalyst delivery
     - 3.1.3 discern the methods for performing catalyst tests
     - 3.1.4 possibility of building a catalyst test stand
   - 3.2 Design
     - 3.2.1 connection of the station to the hydrogen-air mixing system
     - 3.2.2 connection of the station monitoring the basic process parameters of catalysts and

hydrogen incinerators in order to monitor the composition of the obtained hydrogen-air mixture
3.2.3 connection fittings
3.3 Catalyst purchasing
3.4 Catalyst tests
4 Delivery acceptance tests station
4.1 Analysis
4.1.1 possibility of adopting a catalyst test stand for delivery acceptance tests
4.1.2 capitalisation of knowledge on the applicability of catalytic systems for the combustion of materials oxidised in the air
4.2 Design of a station for delivery acceptance tests
4.3 Construction of a station for delivery acceptance tests
4.4 Performance of delivery acceptance tests

PRELIMINARY PROJECT RISK ANALYSIS

Preliminary risk analysis for the process of renovation of hydrogen incinerators was carried out using the FMEmethod [3]. Risk analysis conducted with the use of the FMEmethod focuses on the capability to anticipate an occurrence of an instability in the system or an implemented process based on expert knowledge, as well as preparing in advance ways to respond to materialised risk regardless of the scale of such materialisation[9] [4]. Therefore, this is a method more often applied in technical than economic analysis.

The FME analysis not only contributes to the minimisation of effects of risk materialisation, but also establishes the hierarchy of types of its diagnosed, inherent types, and thus sets the necessary level and direction of monitoring of threats and opportunities. The lack of possibility to ensure secure zones at the $Academy$ is linked to the absence of tradition in conducting tests with the use of hydrogen. Initial model tests at the $Academy$ were conducted with the use of safe hydrogen-air mixtures[10] that did not involve the risk of an explosion[11]. It is now necessary to use streams of mixtures which, for technical and financial reasons[12], should be obtained through the dynamic mixing of hydrogen and air. The intensity of the created threat is high, rated at the level $= 9$ on a ten-point scale.

The relative probability of risk materialisation is also relatively high and estimated at a level $P = 8$ on a ten-point scale. On the other hand, the ideal detection occurs at the level $D_{\%} \cong 100\%$, thus the relative level of probability of detection is estimated at $D = 1$.

The relative risk level RPN[13] does not exceed the critical value $RPN_{kr} = 100$, although it is high and amounts to $RPN = 72$. The responsibility for the preparation of the trial site was entrusted to the project initiator, thus the $Academy$ transferred the risk by lowering the level of the relative risk priority number for the $Academy$ to a negligible $RPN = 8 -$ tab. 6.

The necessity to ensure safety zones is linked to the need for production of large flows of hydrogen-air mixtures by introducing pure hydrogen into the air flow. The intensity of the created threat was assessed to be at the same level as the relative level before, i.e. $I = 9$.

The relative probability of risk materialisation is also relatively high and estimated to be at the level $P = 9$. On the other hand, within this scope the ideal detection occurs, thus its relative level has been estimated at $D = 1$, which corresponds to the detection at the level of $D_{\%} \cong 100\%$. The level of the relative risk priority number (RPN) does not exceed the critical value $RPN_{kr} = 100$, although it is also high and amounts to $RPN = 81$.

The responsibility for the preparation of the trial site has already been entrusted to the project initiator, thus the $Academy$ has transferred the risk of an explosion in its area. Nonetheless, the $Academy$ was still responsible for designing the installation for obtaining hydrogen-air flows, hence the liability is shared by the $Academy$.

The $Academy$ has experience in designing continuous dosing systems, however for small streams. It remains an open issue to develop the skills to quickly design and build such a system. It can be assumed that the relative probability of risk materialisation, taking into account the $Academy's$ experience, may be reduced to a moderate level of $P = 6$, which will enable reduction of the relative risk priority number to the level $RPN = 54$.

The absence of measurement stations is also linked to a lack of tradition in conducting research with the use of hydrogen. As already mentioned, initial model studies carried out at the $Academy$ were conducted with measurement systems that had previously been dismantled and utilised for different purposes. It was now necessary to rebuild them.

The relative intensity of the risk connected to the lack of any possibility of building adequate stations, particularly under the time constraints and with a limited budget, is high and has been estimated at a level $I = 7$ on a ten-point scale.

The relative probability of risk materialisation is also relatively high and estimated to be at the level $P = 8$.

Tab. 4

Risk analysis for the initial project feasibility study.

Type of problem/ problem situation	Effect of risk materialisation	Impact intensity upon risk materialisation *I*	Probable cause of risk materialisation	Probability of risk materialisation *P*	Possibility of detection of risk materialisation	Probability of detection of risk materialisation *D*	*RPN* *RPN=I×P×D*	Applied countermeasures for risk materialisation	Corrected *RPN*			
									I	*P*	*D*	*RPN*
hydrogen dosage system	production of an explosive mix	9	damage	3	possible full detection	5	**135**	implementation research	9	3	3	81
air flow feeding system		9	choking	7	possible ideal detection	1	63	implementation research	9	4	1	36
mixing system		9	insufficient hydrogen expansion	9	possible full detection	2	**162**	implementation research	9	3	2	54
catalyst tests station	incinerator destruction	6	sudden increase of working temperature	7	possible full detection	3	**126**	application of temperature measurements	6	2	3	36
delivery acceptance tests station	production of an explosive mix	9	bad mixing conditions	8	possible full detection	2	**144**	measurements	9	8	1	72
	lack of acceptance of works	10	erroneous measurements	3	possible full detection	3	90	SOP	10	3	2	60

Intensity of generated threat *I*	Probability of occurrence *P*	Probability of detection *D*
1:Almost imperceptible	1: Improbable	1: ideal detection $D_{\%}\cong 100\%$
2-3: Insignificant burden on the customer	2-3: Very little probable	2-5: full detection ($100\%>D_{\%}\geq 99.7\%$)
4-6: Moderate impact	4-6: Small probability	6-8: possible aver. detection ($99.7\%>D_{\%}\geq 98\%$)
7-8: Significant impact	7-8: Moderate probability	9: incomplete detection ($98\%>D_{\%}\geq 90\%$)
9-10: Very significant impact	9-10:High probability	10: lack of detection $D_{\%}\cong 0\%$

***RPN* (Risk Priority Number) - Critical value of relative risk priority number *RPN*>100**

There is a full detection for this type of a risk, hence the relative probability of detection D has been estimated at the level $D = 2$, which corresponds to the detection at the level of $100\% > D_{\%} \geq 99{,}7\%$. The level of the relative risk priority number RPN is slightly above the critical value $RPN_{kr} = 100$ and is equal to $RPN = 112$.

For the purpose of minimisation of the risk materialisation threat, it is necessary to consider the possibility of renting or adapting the available measuring equipment. Since the $Academy$ is the owner of explosimeters whose use may reduce the relative intensity of the risk created, lowering it to the estimated level $I = 3$ and the relative probability of detection to the ideal level $D = 1$, thus causing a reduction in the relative risk priority number RPN to the acceptably low level of $RPN = 24$.

Delays in resolving the problem situation related to the repair of the hydrogen combustion reactors have increased the time pressure. The modernisation of the incinerators needs to be completed within a span of four months. During this period, it is necessary to carry out designs, purchases, build the equipment and conduct catalyst tests. The negative result of these tests will result in the exceeding of the time of bed replacement and the conduction of the delivery acceptance tests. Such a plan has little chance of a punctual performance, even if it is successful at the first attempt.

The project has no time reserve for the repetition of tests hence the relative intensity of risk has been estimated as high $I = 8$. The relative probability of risk materialisation is also critical, hence it has been estimated to be at the level $P = 9$. On the other hand, the detection was assessed to be at a full level of $100\% > D_{\%} \geq 99{,}7\%$, which corresponds to $D = 2$. The level of relative risk priority number RPN exceeds the critical value $RPN_{kr} = 100$ and amounts to $RPN = 144$.

However, the capitalisation of knowledge related to equipment construction, in particular the submarine atmosphere monitoring system, within the framework of the project financed by the Polish MoD Armament Policy Department no. 48 / MW/S-50/99 dated as of 29.12.1999 allows to reduce the relative probability of risk materialisation to a very unlikely level amounting to $P = 3$ and the detection within this range should be defined at the ideal level of $D = 1$, hence the relative risk priority number RPN will be significantly reduced to the level of $RPN = 24$.

The limited amount of time available for conducting the tests has an important effect on the risk of project failure, thus the relative intensity of the threat generated is estimated at the level of $I = 7$ on a ten-point scale. The relative probability of risk realisation is nearly certain, hence it has been estimated to be at the level of $P = 9$. The detection equipment is also nearly complete, hence the relative probability of detection has been estimated at the level of $D = 2$. The relative risk priority level RPN does not exceed the critical value $RPN_{kr} = 100$, although it is high and amounts to $RPN = 126$.

The only way to minimise the value of relative risk priority number RPN is to include relevant reservations in the contract. However, since it is known that the risk will become materialised, it can be concluded that $D = 1$, therefore, the relative risk priority number is well below the critical value and amounts to $RPN = 63$.

The greatest diagnosed risk that can be materialised is that related to the budget constraints of the project.

From the general point of view of project management there is a certain compromise between: project scope, budget, time and quality. With rigidly defined scope and a significant time limitation an increased budget can ensure project fulfilment in compliance with critical quality requirements CTQ.

However, the considered project is characterised by a rigid scope, time limitation and a limited budget, thus it should not be expected that the quality requirements CTQ will be met at a high level. The relative intensity of the generated threat of risk materialisation due to the low project budget was assumed to be at a very high impact level $I = 9$, whereas its materialisation at the upper level of moderate probability $P = 8$ on a relative ten-point scale. However, only average detection at the estimated relative probability level of $D = 5$ is possible. The level of relative risk priority number RPN substantially exceeds the value of critical risk priority number $RPN_{kr} = 100$ and amounts to $RPN = 360$.

By knowledge capitalisation and approval of the catalyst price by the project initiator, the relative probability of risk materialisation with a low project budget may drop to a low level of $P = 6$, and for the same reason relative detection may come close to the ideal $D = 1$, thus allowing the limitation of the relative risk priority number to the level of $RPN = 54$, i.e. below the critical limit of $RPN_{kr} = 100$.

The risk associated with a low budget is closely linked to the risk of a lack of decision concerning the choice of a catalyst supplier and acceptance of its terms and conditions, as it was stated above. The relative intensity of the threat posed by this risk is high and estimated at the level of $I = 8$ with a high relative probability of its materialisation $P = 9$. The relative probability of detection is high provided that those in charge of the procurement of the necessary parts remove the barriers which are preventing acceptance of a supplier and its terms.

Because this condition was met, the relative probability of detection was assumed to be at $D = 1$. The relative risk level RPN does not exceed the critical value, although it is high and amounts to $RPN = 72$. With the contractor's acceptance of an establishment of a checkpoint and the capitalization of knowledge connected with possible catalyst suppliers, it is expected to be possible to reduce the level of relative probability of materialisation of the risk associated with the lack of acceptance of the catalyst supplier on its terms from high $P = 9$ to unlikely $P = 5$, which results in a further decrease in the relative risk priority number to the level of $RPN = 40$.

With the $Academy's$ experience in the construction of measuring systems, the lack of equipment supplier does not pose major problems. The relative intensity of risk posed by the threat was estimated at a moderate level of impact of $I = 6$. The relative probability of risk materialization is small, since the producer may also be the $Academy$, hence it amounts to $P = 4$. However, at the project commencement, the possibility of detection of the risk of a lack of equipment suppliers was incomplete, hence at a relative scale its level was estimated at $D = 3$. The relative risk level RPN does not exceed the critical value, although it is high and amounts to $RPN = 72$.

However, considering that the experience of the $Academy$ will allow building of the entire required equipment, the relative level of detection can be considered ideal $D = 1$, which leads to a reduction in the relative risk number to the level of $RPN = 24$.

Preliminary analysis of the likelihood of the potential risks demonstrates that with the co-operation with those responsible for procurement, the project has a chance to adapt to accommodate the identified risks. It should be noted that the project is risky enough that it may be considered wise to not take it up. That said, the economic considerations associated with maintaining the prestige of the *Academy* should contribute to the taking of the decision to initiate such a risky project.

SUPPORT

Project support was to be ensured by procurement services and organisation of sites for research and delivery acceptance test stations. The responsibility for carrying out support was assumed by the project initiator.

KEY STAKEHOLDERS

Due to the nature of the project, it was relatively easy to identify key stakeholders; these were defined during the work of the project team as a result of the activities of the *FG* group[14] with the use of the *Delh i meth od*[15]. In addition to the project initiator, it is also necessary to take into account the District Military Office ensuring fulfilment of quality requirements *CTQ*.

However, it should be remembered that the main project stakeholder is the crew of the submarine and its administrator.

GENERAL PROCESS MAP

A high-level process map *SIPOC*[16] was established by members of the procurement team whilst carrying out their activities with the FG group using

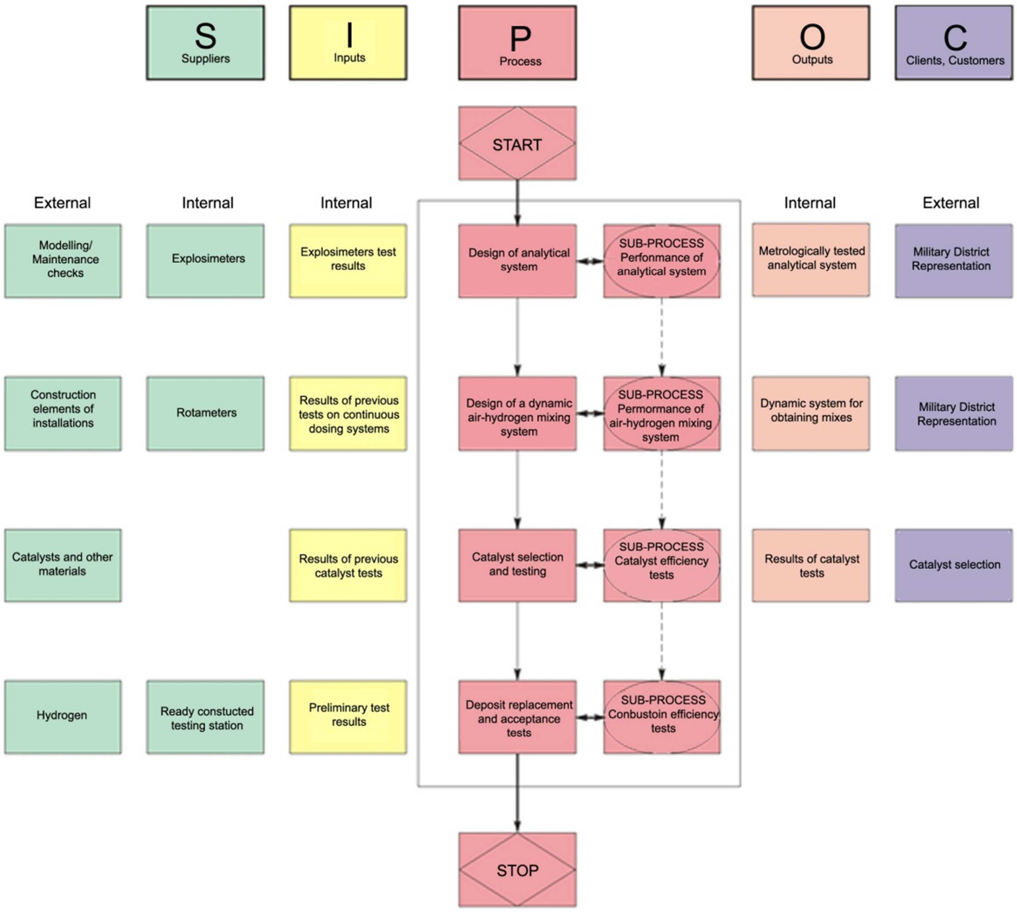


Fig.1 Process map in the form of a diagram *SIPOC*.

the *Delhi method* and *brainstorming sessions* – fig. 1. The map shows the project implementation process and the system it runs in, along with the inlets and outlets. The prevailing system is made up by users from the *Polish Navy*. The project has been rationalised for the purposes of the submarine renovation process.

It should be noted that the project implementation plan assumes the construction of a station dedicated to carrying out delivery acceptance tests along with its gradual development. Two research stages are related to the construction of technology demonstrators[17]:

- device for controlled hydrogen dosage,
- device for controlled air stream emission.

Subsequently, their tests, the construction of a system for monitoring the basic process parameters and operation of the incinerators, will enable setting up of a station for catalyst tests which will later be rebuilt into a delivery acceptance test station. Hence, the process map indicates sequential sub—processes in the construction of the required equipment to carry out repairs and delivery acceptance tests on the hydrogen incinerators.

QUALITY ASSURANCE

Defining of the critical requirements of the main stakeholders from the point of view of quality CTQ was performed with the use of the *brainstorming method*.

It resulted inthe determination of the following nine requirements: probity/ accuracy, relevance, compatibility, being maintenance-free, efficiency, reliability, experience/SOP[18], redundancy.

The defined project is characterised by a very strict schedule which under normal conditions makes it impossible to implement the defined scope without spare parts, including a fresh catalyst and replacement technology. If such circumstances do not occur, as it is in this case, it is necessary to establish a surplus budget. The surplus budget allows for the purchasing of eligible services or*the know-how*. However, in the discussed project the budget is also limited. The limitations of time, scope, and budget must result in quality deterioration — fig. 2.

As shown by the risk analysis, it would be impossible to take up such a project under normal circumstances without the project initiator's agreement to significantly increase the budget and guarantee a high contractual insurance. For prestige reasons, it was decided to take up the task with the reservation of maintaining only the minimum level of quality.

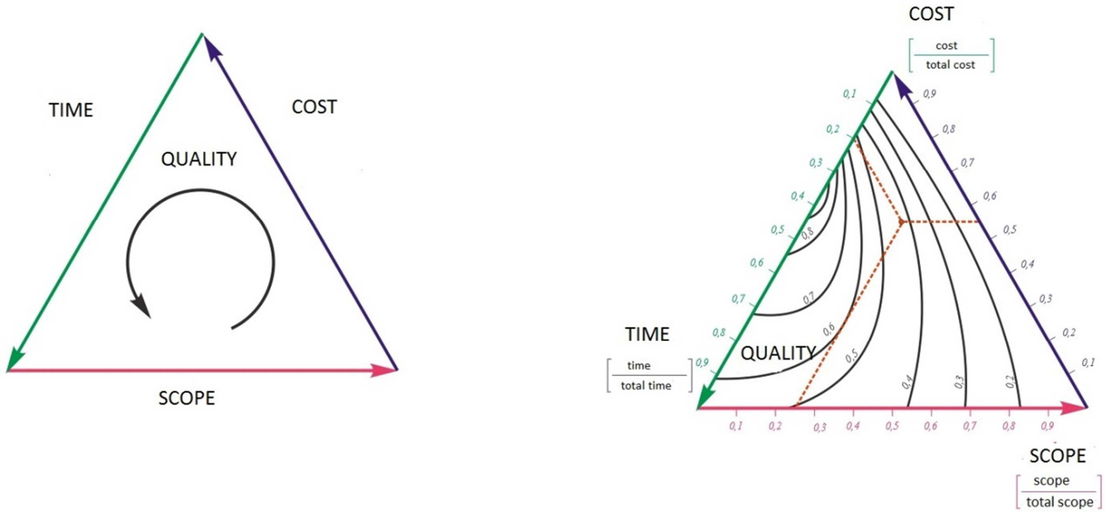


Fig. 2 The relationship between the cost, time, scope and quality in the project.

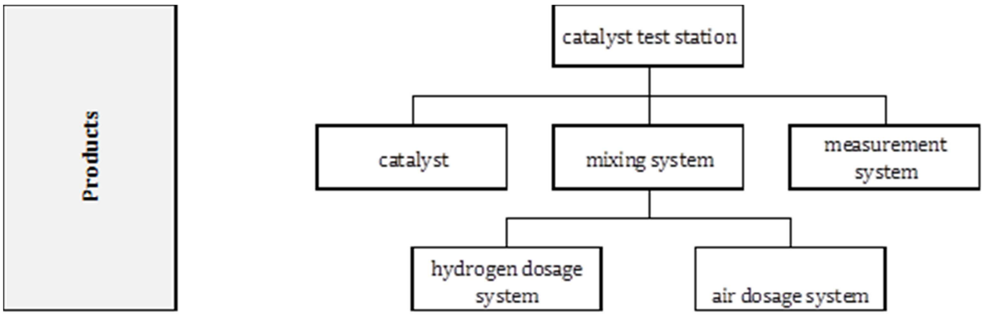
PRODUCT STRUCTURE

The initial determination of the product division structure was made during a high-level project analysis. The following necessary key intermediary products were identified as having not been delivered for the acceptance of the project initiator. Systems used for:

- monitoring of hydrogen content,
- obtaining hydrogen-air mixtures,
- performance of catalyst efficiency tests,
- delivery acceptance tests.

These products are not included in the current project scope, however their absence will not allow achievement of the main purpose of the project. The product subjected to delivery acceptance tests and acceptance consists of four hydrogen incinerators. Intermediate products have been hierarchised and their relationships with the defined quality requirements CTQ have been identified. The results of this analysis are shown graphically in Fig. 3. Horizontal designs are based on project requirements, vertical on quality requirements CTQ, whereas the designs based on specific process requirements for the established quality requirements CTQ constitute cells of the matrix presented in fig. 3.

The main product is the catalyst test station. Due to the fact that catalyst tests will be conducted on a real vessel, it will probably be possible to use the catalyst tests station also as a site for carrying out the delivery acceptance tests.



CTQ / Processes	1.accuracy/probity	2. currency	3. adequacy	4. compatibility	5. maintenance free(n	6. efficiency	7.reliability	8. experience/ SOP	9. redundancy
A. Catalyst tests	X		X	X			X	X	
B. working parameters measurements	X	design based on specific requirements	X	X	X	X			X
C. mixing air with hydrogen			X	X			X		
D. air dosage						X	X		
E. hydrogen dosage	X	design based on process requirements				X	X		

design based on process requirements

design based on quality requirements

Fig. 3 Basic products of an improved process and their relationship with the basic quality requirements CTQ.

Process-based horizontal designs make up a hierarchically structured pyramid of particular intermediate products that are essential to the project, however do not constitute elements that are subject to the project initiator's acceptance procedure. Also the *know – how* acquired during the development of partial products constitutes proprietary knowledge belonging to the contractor.

The ability to accurately dose hydrogen is the basis of safely conducted tests. The performance of tests using the ordered hydrogen / air mixtures is pointless, not only due to the significant cost, but also the need for building high-performance equipment for their controlled release.

Gas cylinders would have to be connected into bundles and these would not normally be utilised for hydrogen-air mixtures. Therefore, the most convenient way is to produce mixtures by the dynamic mixing of hydrogen withair.

For the precise adjustment of the flow of dispensed hydrogen, a regulating system with a co-operating nozzle was used for supercritical flows. Such systems are used in diving apparatuses with semi-closed respiratory circuits. Due to the fact that the *Academy* has conducted research in this area it has proper competences todesign such systems. Measurements of gas flows will be carried out using rotameters. After determining the dependence between the pressure of the nozzle feed in the function of a supercritical stream for the hydrogen emitted by the nozzle, the flow control will be performed by the measurement of the nozzle feed pressure [5].

Air dosage will be initially implemented with the help of life preservation systems available at the *Academy's* hyperbaric complexes. These systems are equipped with high capacity displacement pumps controlled by inverters. This allows for a sufficiently precise regulation of the airflow. The air flow control will be rotametric.

Mixing of the air with hydrogen will be carried out in the inlet pipe of the incinerator. It is necessary to experimentally check the distance until the mixing of hydrogen and air is complete.

The basic measurements of working parameters include the determination of hydrogen content before and after the incinerator. In addition, it is useful to measure the temperature of the bed and preheating. Measurements of hydrogen content are crucial from the point of view of work safety and as parameters used to assess the efficiency of incinerator operation in the course of delivery acceptance tests.

Catalyst tests and subsequent delivery acceptance tests will be conducted using the fan and incinerator from the submarine's existing equipment. In addition, measurement equipment and a mixer for the production of hydrogen-air mixtures will be used.

The graph presented in fig. 3 illustrates an estimation of the impact of major quality requirements CTQ on sub-processes— which guarantee an adequate direction for the main process: the modernisation of hydrogen incinerators. The conducted qualitative analysis of mutual relationships of the processes with the established critical quality requirements CTQ, for the leading process constitutes the basis of quantitative analysis of such relationships.

PROBLEM SITUATION

The description of the project included an initial diagnosis, the objectives set for the Team in connection with conducting the modernisation of the hydrogen incinerators as well as potential hazards of the project's failure.

What are the disadvantages of hydrogen combustion in incinerators?

The incinerators have exceeded their service life between mandatory renovation works, hence their work may be characterised by low hydrogen combustion efficiency. Most likely, the catalyst has partially lost its effectiveness as a result of an exposure to atmospheric pollution, e.g. it has been "contaminated" with sulphur compounds.

When and where did the problem situation arise?

The problem situation was reported by the crew and accepted for resolution during the submarine's overhaul. As part of the investigation, the effectiveness of the incinerators was put to the test and it was the outcome of this investigation that served as the basis for the decision to either modernise or scrap them.

The verification was not carried out by the *Academy*. The *Academy* only received an order for a repair without a verification, indicating the replacement of the catalyst bed with a local equivalent, originating from the EU or North America.

How extensive is the problem situation?

The problem situation is serious as the *Academy* lacks a database andexperience in catalyst research. The skills in this area were gained by the project manager 30 years ago while working at *the Institute of Low Temperatures and Structural Research of the Polish Academy of Sciences* and a model research within the framework of the project convened by the Polish MoD's Armament Policy Department, agreement no. 20/DPZ/3/OTM/S/WR/MON/2002/706 entitled: "Life support system on a submarine" implemented in the years 2002–2004 at the *Academy*.

The primary problem is the choice of the catalyst type that will work correctly in the incinerator configuration. Should the granulation / shape of catalyst tray be different from the original, it needs to be ensured that it does not cause a much larger flow resistance, thus guaranteeing proper ventilation of the battery compartments.

The effectiveness of the catalyst used must be confirmed during tests conducted in conditions approximated to the actual use of hydrogen-air mixtures, while maintaining parameters similar to those specified in the technical documentation of hydrogen incinerators.

For the purpose of testing, it is necessary to develop measurement methods as well as a system for the preparation and administration of appropriate hydrogen-air mixture flows.

What is the impact of the problem situation on the activities of the Armed Forces?

The submarine crew sees the problem as a priority, although most submarines are not equipped with such a system.

KEY ISSUES AND THREATS TO PROJECT IMPLEMENTATION

The basic issues of the project and potential threats to its implementation were identified.

Is the diagnosis of the problem situation based on the observed facts or assumptions?

The diagnosis is based on the assumption that the catalyst bed does not reveal proper catalytic activity. Such a statement was reported to the *Academy*.

Is the problem situation trivial and requires merely a correction?

The problem situation is not trivial as it requires selectionand checking of the effectiveness of the catalyst which is to replace the old bed. Therefore, the project consists of the following phases:

- Industrial research being part of scientific research, aimed at acquiring new knowledge and skills to develop new products, processes, services, and improve the existing processes and services. The said research encompasses the development of components of complex systems, in particular for the assessment of the suitability of generic technologies, with the exception of prototypes included within the scope of the development works.
- Development works consisting in the acquisition, integration, shaping and use of the currently available knowledge in the area of science, technology and business activity, as well as other types of knowledge and skills to create and design new, modified or upgraded products
- Provision of research and development services in the area of techniqueand technology. Unlike the conducted research and development works, scientific and research services are liable to VAT taxation.

All of the above phases should be carried out in an extremely short time span.

Has the data for the analysis of the problem situation and verification of the proposed solutions been collected by an appointed team?

The data for the analysis of the problem situation must be collected as part of the project.

Does the problem situation not involve too extensive a process which should be divided into smaller sub−processes?

In order to check the efficiency of the selected catalyst it is necessary to set up a specialised station which the *Academy* currently lacks, thus it must be built within the scope of the project. Intermediate stages of work are not of interest to the project initiator, hence the project-developed $know-how$ will remain the sole property of the $Academy$, however it will also not be allocated a separate funding in the framework of the project. The investment in research is to a large extent comprised of an own contribution of the project team and their effort will not be rewarded proportionally to their involvement.

Is the solution to the problem situation no longer included in its definition?

The definition of the problem situation does not contain a solution. The proposed project course along with intermediate products was developed only as a result of a preliminary analysis of the problem situation within the framework of the project.

Has the project implementation been accepted by the main stakeholders?

The assumptions concerning the phases, intellectual property, method of work acceptance and support in the implementation of the project have been approved by the project initiator. The scope of the project provides for the following arrangements:

- the modernisation of hydrogen incinerators will be carried out separately and the $Academy$ will perform only their upgrade consisting in catalyst bed replacement,
- the cost for the purchase of selected catalyst types at the indicated supplier will be picked up by the project initiator,
- the purchases of materials for the construction of the stations for both catalyst and delivery acceptance tests will be paid for out of project costs,
- a choice of location and installation of test stations at the project initiator's premises and risk,
- the developed $know-how$ will remain with the $Academy$, which will grant its licence for the application of the solution for four modernised incinerators.

CONCLUSIONS

The process definition phase ended with the following results:

- definition of the product and system under improvement, namely the process of hydrogen incinerator modernisation with simultaneous determination of sub−processes from which intermediate products emerge,
- translation of the identified customer requirements into the following quality requirements CTQ: probity/ accuracy, punctuality, adequacy, compatibility, being maintenance-free, efficiency, reliability, experience/SOP, redundancy,
- development and approval of the design team card for which the competences have been defined and in which the financing for development solutions is assured - until their implementation,
- definition of a high-level process map that identifies the context and system associated with the modernised process as well as other processes running on that system, as shown in fig. 1,
- identification of basic process products, i.e. modernised hydrogen incinerators,
- hierarchisation of intermediate products and their reference to quality requirements CTQ, whose structure was ordered and presented graphically in fig. 3.

An additional element of the presented definition phase consisted in the performance of an initial project risk analysis, which was used to both support the business case for the project, and eliminate certain risks by making reservations in the contract for the acceptance of residual risk for the project.

PROCESS MEASUREMENT PHASE

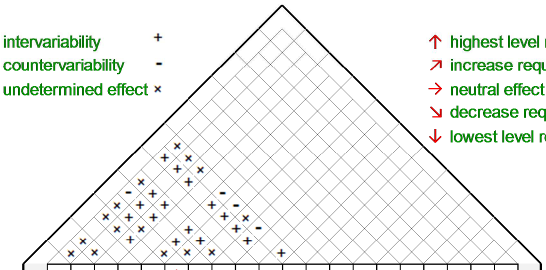
During the measurement phase, hierarchisation was performed with the use of the QFD method[19] on the diagnosed[20] quality requirements CTQ for the considered modernisation process of the hydrogen incinerators. Preliminary risk analysis for the project implementation process was performed using the $FMEA$ method.

The major response was determined during the delivery acceptance tests. The analysis of the measurement system was proposed and conducted for the planned tests and trials. A data collection plan was established and measurement process efficiency standards were defined.

Quality Function Deployment
CTQ quality planning
Quality assurance in the modernisation of hydrogen incinerators $PD-3A$

intervariability +
countervariability -
undetermined effect ×

↑ highest level required
↗ increase required
→ neutral effect
↘ decrease required
↓ lowest level required



Wymagania jakościowe Critical to Quality (CTQ)

Powiązania wymagań dla produktu i wymagań odbiorcy (9-wysokie; 3-pośrednie; 1-niskie; 0-brak związku)

	Customer requirements	←score 1-5	accuracy/probity	currency	adequacy	compatibility	maintenance freeness	efficiency	reliability	experience and SOP	redundancy	Maximum value
			↗	↗	↗	↗	↑	↗	↗	→	↘	
Products/Processes	catalyst selection	5	9	3	9	9	0	3	9	9	1	9
	H2 conc. & incinerator parameters measurement system	5	9	3	9	9	9	9	9	3	9	9
	H2 dosing system	3	9	1	1	1	3	9	9	3	1	9
	air flow production and measurement system	3	3	3	3	3	3	9	9	3	1	9
Safety	hydrogen-air mix production	5	3	1	9	9	3	3	9	3	1	9
	H2 combustion	5	9	1	9	3	0	0	9	3	0	9
	incinerator exploitaition	5	9	1	3	3	9	0	9	3	0	9
Support	market identification	3	9	9	9	9	0	3	9	3	3	9
	purchasing	2	9	9	9	9	0	0	9	3	0	9
	Shipyard support in project risk minimisation	4	9	9	9	0	0	9	9	3	3	9
	Quality requirements hierarchy		312	138	288	222	123	174	360	150	82	360
	Quality requirements threshold values		$\Delta C_{H_2} \leq 0,2\ \%_v$	not older than 10 years	adjustment >90%	possibility of use ≅ 100%	service intervals > 1 year	more than >90%	sufficienty ≅ 100%	sufficient ≅ 100%	zero redundancy	Maximum value
	Indicators of difficulty in quality achievement (scale 1-5)		4	3	5	2	2	3	4	3	1	5
	Quality requirements ranking		1248	414	1440	444	246	522	1440	450	82	1800

Competition products ranking - benchmarking: 1 | 2 | 3 | 4 | 5

1: $0 \leq Ranking < 360$
2: $360 \leq Ranking < 720$
3: $720 \leq Ranking < 1080$
4: $1080 \leq Ranking < 1440$
5: $1440 \leq Ranking \leq 1800$

Fig. 4 Customer requirements and critical quality requirements CTQ for the modernisation process on hydrogen incinerators.

CUSTOMER REQUIREMENTS

The QFD diagram presented in fig. 4 was used to define the critical requirements $CTQ$of the main stakeholders, as well as quality requirements.

During further analysis, this diagram will be developed from the version of quality planning and determination of quality requirements CTQ through product and process planning up to the implementation phase.

By means of group work, three areas of implementation of the modernisation process on hydrogen incinerators were determined:

- necessary products and intermediate processes for project implementation,
- ensuring safety during work implementation,
- scope of support and co-operation of the project initiator,

The following intermediate processes needed to implement the project were defined:

- catalyst selection,
- construction of a measurement system for hydrogen concentration and incinerator parameters,
- construction of a hydrogen dosage system,
- construction of a system for the production and measurement of air flow.

The project initiator has acknowledged intermediate products and processes as internal problems of the $Academy$. Final inspection of the effect of the modernisation of the hydrogen incinerators will consist in an unquestionable detection of at least a tenfold decrease in the hydrogen content in the air-hydrogen mixture fed to the incinerator with the hydrogen concentration of approximately $C(H_2) \cong 3\%_v$.

The project initiator has consented to the financing and implementation of all three processes preceding the overhaul of the hydrogen incinerators as well as the scope of necessary intermediate products and processes needed in the project implementation – fig. 3.

QUALITY ASSURANCE

The earlier diagnosed critical requirements[21] for the assurance of quality CTQ were analysed using the QFD method to determine their ranking. The three most important ones are:

- probity/accuracy,
- adequacy,
- reliability.

The analysis of the quality requirements CTQ conducted in relation to the process of modernisation of the hydrogen incinerators enabled the determination of their ranking with regard to the difficulty in the obtainment of the minimum level – fig. 4. The ranking was determined on the basis of the maximum number of points in the hierarchy of customer requirements, links to the quality requirements CTQ and the likelihood of fulfilment of the threshold values of those quality requirements CTQ.

Taking into account the imposed quantitative requirements CTQ for the products, there was no overestimation of the ranking of the basic critical requirements for quality assurance CTQ by identifying the same three most important ones: probity/accuracy, adequacy, reliability.

OPERATIONAL DEFINITIONS FOR QUALITY REQUIREMENTS

Fig.4 lists 9 key quality requirements CTQ for the modernisation process on the hydrogen incinerators: probity/accuracy, relevance, compatibility, being maintenance-free, efficiency, mobility, experience, SOP and redundancy which are defined below with the characterisation of the types of data, goals, tolerance limits, etc.

- probity/accuracy is understood as the reliable and accurate measurements of hydrogen content in the air, and the accurate and safe methods for obtaining significant amounts of hydrogen-air mixtures ensuring a stable flow of the supplied hydrogen-air mix,
- currency is understood as meaning the most modern solutions,
- adequacy is understood as effective market identification and application of the best solutions in the construction of the stations and the selection of the most appropriate catalyst,
- compatibility is understood as the compatibility of the market survey with the requirements set for the catalyst and the purchases of the catalyst and components of test benches,
- maintenance freeness is understood as lack of a need to hire qualified personnel to identify the catalyst market, and lack of a need to engage qualified personnel to ensure explosion protection during the operation of the system for the production of hydrogen-air mixture and hydrogen incinerators,
- efficiency is understood as the qualified support from the project initiator in the implementation of the project, and the assurance of the production of appropriate quantities of a high-quality hydrogen-air mixture,
- reliability is understood as an optimal market survey, with purchasing and support provided by the project initiator and optimal selection of catalyst, all subsystems, the station for the performance of catalyst and delivery acceptance tests,
- experience and SOP are understood as a sufficient capitalisation of knowledge,
- redundancy is understood as equipment surplus ensuring operational safety.

Reliability and accuracy should guarantee:

- Measurement of hydrogen content in the air for the range of hydrogen content C_{H_2} within the limits of $C_{H_2}=[0;4]\%_v$ with accuracy guaranteeing the absolute error at the level of $\Delta C_{H_2} \le 0{,}2\ \%_v$.
- Accurate and safe methods for obtaining large quantities of hydrogen-air mixtures ensuring a stable flow of hydrogen-air mixture to be supplied within the limits of the air flow at the level up to $\dot{V}_0 \in [0;\ 150]\ m^3 \cdot h^{-1} \triangleq [0;\ 2500]\ dm^3 \cdot min^{-1}$ and hydrogen flow within the limits of $\dot{V}_{H_2} \in [0;\ 4{,}5]\ m^3 \cdot h^{-1} \triangleq [0;$

75] 〚dm〛^3·〚min〛^(-1). The accuracy of the preparation of the said mixtures does not need to be strictly specified as their composition will be measured by the measurement system dedicated for the supplied hydrogen-air mixture. However, the scope of content regulation by the adjustment of air and hydrogen flow should ensure the production of hydrogen-air mixtures with an accuracy suited to measurement capacity.

Currency should guarantee possibly the most up-to-date solutions for the proposed catalyst type, its testing stations containing safe and modern measurement systems and a safe and efficient system for the production of hydrogen-air mixtures of the required composition. Generally, the proposed solutions should represent technology not older than 10 years, especially with regard to the available catalyst types to ensure its delivery in the nearest time perspective.

Of course, older solutions are acceptable if they are still considered to be the current state of the art[22]. Currency will be evaluated on the basis of expertise acquired fromscientific publications on specific issues.

Adequacy should ensure effective market identification and application of the best solutions in the construction of test stations and the selection of the most suitable catalyst, constituting generally applicable state of the art technology, not older than 10 years. Adequacy will be estimated in terms of suitability for the hydrogen incinerator construction in the extent above $\geq 90\%$, with consideration of the possibility of applying the most advanced technology. Adequacy will be assessed on the basis of expert knowledge and subsequent measurements when assessing the parameters of the constructed stations, and on the efficiency of hydrogen combustion by the modernised incinerators.

Compatibility should guarantee the compliance of replacement components identified via the market survey with the requirements specified for the catalyst. It should also establish purchasing expectations for both the catalyst and components of test stations, guaranteeing their required quality, the efficiency of the system of obtaining hydrogen-air mixture, proper catalyst selection for the renovated hydrogen incinerator and a suitable measuring range for hydrogen content monitoring. Such compatibility will only be estimated on the basis of expertise and should be at a level close to full compliance $\cong 100\%$.

The fact that the system is maintenance-free should ensure the lack of a necessity to employ qualified personnel to identify the catalyst market. In technical systems, this quality should ensure the operation of systems without the need for servicing by personnel qualified in explosion protection devices during the operation of the hydrogen-air mixture systems and incinerators for a period of not less than 1 year.

Efficiency should be linked to the provision of qualified support by the project initiator in the implementation of the project consisting in the provision of a trial site and realisation of purchases for the project. Technically, it involves the provision of adequate hydrogen and air yield in the production of adequate quantities and qualities of hydrogen-air mixtures at the estimated reference level to the maximum flows required in delivery acceptance tests to an extent greater than $> 90\%$.

Reliability should ensure the optimum survey of markets, purchases and support provided by the project initiator in the course of project implementation, and ensuring availability of a trial site. From the technical side, it should ensure optimum catalyst choice, all stations for catalyst testing and carrying out delivery acceptance tests at an estimated reference level of approximately $\cong 100\%$.

Experience and SOP should guarantee sufficient capitalisation of knowledge for the correct selection of an adequate catalyst at an estimated relative reference level of approximately $\cong 100\%$.

Redundancy should be ensured at such a level as to guarantee the safety of work with hydrogen-air mixtures. The said safety is based on suitable measurement capacity of hydrogen content. Redundancy assessment is based on an estimation of the reference level for incinerators. The required redundancy level approximately amounts to $\sim 0\%$.

THE RELATIONSHIP BETWEEN REQUIREMENTS

Improved probity/accuracy of operations usually causes their decreased efficiency. This is also the case in relation to purchasing and system construction. It does not have a greater impact on hydrogen measurements. Measurement accuracy, on the other hand, is linked toexperience and correct SOP, as well as being proportional to purchases and system construction– fig. 4.

The currency of measuring systems is usually related to greater freedom from maintenance, efficiency and reliability for newly designed systems. Typically, newly designed systems are also characterised by internal redundancy consisting in self-monitoring of the measuring system that generates device status messages and, in rare cases, allows the possibility of an emergency transition to a backup measurement system.

This is not the case in the discussed situation. System redundancy has been ensured by the provision of additional explosimeters and temperature measurement systems that can be replaced at any time. Moreover, an expedited order implementation path has been ensured for explosimeters and spare parts, as was the possibility of renting an explosimeter outside the $Academy$. Such a procedure resulted from a very short project implementation time.

Additionally, a fast way of implementation was ensured with regard to eligible metrological services in relation to their operational checks and calibration. The assurance of currency evaluation is strictly related to the possessed experience and SOP which are either present in the organisation or must be provided in the form of external services. Experience and SOP related to the working with measurement systems seems to be sufficiently internally secured. It is necessary to reconsider the need to acquire additional competences in relation to working with explosive hydrogen-air mixtures, as such experience is lacked by the $Academy$.

Adequacy in terms of effective market identification is closely related to the compatibility of the new catalyst with the hydrogen incinerator construction ensuring sufficient levels of efficiency and reliability. The adequacy of the selected catalyst can be determined on the basis of our own experience and SOP, or based on experience and SOP of external experts. The knowledge gap in this area has been diagnosed, hence it is undoubtedly advisable to obtain experts' support.

A similar issue concerned with adequacy should be considered when it comes to the application of the best solutions for the construction of test stations. It seems that the $Ac\ a\ demy$ has sufficient competences to build measurement stations that will ensure their compatibility, performance, reliability, or redundancy based on experience and SOP.

However, through carrying out tests it is necessary to fill in the gaps in experience in order to make it possible to establish appropriate compatibility, efficiency and reliability in the production of air-hydrogen mixtures guaranteeing safety of the tests conducted on catalysts as well as delivery acceptance tests on the hydrogen incinerators.

In general, for mature systems or technologies, there is a tendency of decreasing redundancy – redundancy being an expensive security for still underdeveloped, unreliable technologies[23]

Compatibility is assessed on the basis of experience and SOP. The greatest problem in the project lies in the assessment of catalyst compatibility with the construction of hydrogen incinerator $PD-3A$ which may result in the need for hiring external experts.

The relationship between the maintenance-free aspect and currency has been described earlier. The prerequisite that the system is maintenance-free, is understood as meaning that there is a lack of need to hire qualified personnel to identify the catalyst market, and a lack of need to engage qualified personnel to ensure explosion safety during the operation of the system for the production of hydrogen-air mixtures, and hydrogen incinerators, is inherent with reliability.

Only highly reliable technologies allow minimisation of the need for supervision and a reduction in redundancy. The level of possible maintenance-freeness can be estimated on the basis of experience and SOP. It seems likely that it will be possible to estimate it on the basis of tests and trials conducted within the scope of the project without the need to involve external experts.

Performance related to purchasing will be ensured through the support of the project initiator as their own logistic services possess extensive experience in this area.

Ensuring adequate yield of hydrogen and air flow in the production of adequate volumes of hydrogen-air mixtures is strongly linked to the experience and SOP of the $Academy$. Other links to currency, adequacy and compatibility have been discussed above.

Reliable market identification, purchasing execution and support in project implementation are strongly linked to the previously described experience of the project initiator and the possessed SOP procedures. As previously pointed out, the negative correlation between reliability and redundancy seems obvious.

The relationship between reliability, currency, adequacy, compatibility and maintenance freeness has also been described before. Like other quality requirements CTQ, reliability level is pre-evaluated on the basis of experience and SOP, and later on the basis of tests. However, the optimum choice of a catalyst, all its subsystems and the delivery acceptance testing station must be based on the $Academy's$ knowledge and experience with the possibility to consult external experts.

Redundancy understood as equipment surplus guaranteeing safety of work can be assessed through experience and SOP. However, in this respect the $Academy's$ experience must be preceded by studies of relevant literature and, where appropriate, by knowledge of external experts. Other connections to requirements (CTQ for experience, SOP and redundancy) are described above.

HIERARCHISATION OF THE IMPACT OF REQUIREMENTS

Critical quality requirements CTQ for products have been systematised in terms of their impact and controllability. The results of this analysis are summarised in tab.5.

From the results collected in tab.5 it stems that not all of the CTQ can be directly controlled in terms of their influence. Some of the key effects are only subject to limited[24] inspection, having an influence both on the quality of the overhaul process as well as subsequent operation of the hydrogen incinerators.

RISK ANALYSIS IN RELATION TO QUALITY REQUIREMENTS

Risk analysis for the process of renovation of the hydrogen incinerators was carried out using the $FMEA$ method [3].

Tab. 5

Tabular summary of impact for the analysed qualitative requirements CTQ for the process of renovation of hydrogen incinerators $PD-3A$.

		EFFECT		
		High	Medium	Low
CONTROL	Feasible	Adequacy Maintenance freeness Precision Efficiency	Redundancy	Currency
	Incomplete	Experience and SOP Reliability Probity	Compatibility	

Tab. 6

Risk analysis for the requirements set in relation to the modernisation of hydrogen incinerators .

Type of problem/ problem situation	Effect of risk materialisation	Impact intensity upon risk materialisation	Probable cause of impact materialisation	Probability of risk materialisation	Possibility of detection of risk materalisation	Probability of detection of risk materialisation	*RPN*	Applied countermeasures for risk materialisation	Corrected *RPN*				
		I		*P*		*D*	*RPN=I×P×D*		*I*	*P*	*D*	*RPN*	
Accuracy/probity assurance	production of an explosive mix	9	improper measurement process	3	possible average detection	6	**162**	metrological tests	9	1	6	54	
		9	significant hydrogen release	6	possible full detection	5	**270**	reliable measurement + nozzle system	9	3	2	54	
		9	air flow obstruction	4	possible full detection	2	72	SOP	9	3	2	54	
		9	bad mixing conditions	8	incomplete detection	9	**648**	research & SOP + measurement system	9	3	3	81	
Currency assurance	catalyst unavailability	10	unpunctual delivery	9	incomplete detection	9	**810**	use of remaining catalyst parts	8	9	2	**144**	**RPN too high**
		10	upunctual delivery	9	incomplete detection	9	**810**	activation of the old catalyst	6	9	2	**108**	**RPN too high**

Intensity of generated threat *I*	Probability of occurrence *P*	Probability of detection *D*
1: Almost imperceptible	1: Improbable	1: ideal detection $D_{\%}\cong 100\%$
2-3: Insignificant burdent on the customer	2-3: Very little probable	2-5: full detection ($100\%>D_{\%}\geq 99.7\%$)
4-6: Moderate impact	4-6: Small probability	6-8: possible aver. detection ($99.7\%>D_{\%}\geq 98\%$)
7-8: Significant impact	7-8: Moderate probability	9: incomplete detection ($98\%>D_{\%}\geq 90\%$)
9-10: Very significant impact	9-10: High probability	10: lack of detection $D_{\%}\cong 0\%$

RPN **(Risk Priority Number) - Critical value of relative risk priority number *RPN*>100**

Tab. 6 contd.

Risk analysis for the requirements set in relation to the modernisation of hydrogen incinerators .

Type of problem/ problem situation	Effect of risk materialisation	Impact intensity upon risk materialisation	Probable cause of risk materialisation	Probability of risk materialisation	Possibility of detection of risk materialisation	Probability of risk materialisation	*RPN*	Applied countermeasures for risk materialisation	Corrected *RPN*				
		I		*P*		*D*	*RPN=I×P×D*		*I*	*P*	*D*	*RPN*	
Currency assurance	lack of a mix production system	9	too complicated construction	4	possible full detection	3	**108**	implementation research	9	2	2	36	
Adequacy/compatibility assurance	insufficient market identification	7	outdated manufacturer data-bases	3	incomplete detection	9	**189**	joint search	7	2	7	98	
	catalyst unsuitable for the incinerator	9	different catalyst granulation	8	possible full detection	2	**144**	implementation research/construction modification	3	8	2	48	
Assurance of required level of maintenance freeness	production of an explosive mix	9	malfunctioning measurement system	4	possible average detection	7	**252**	research	9	3	3	81	
Assurance of proper efficiency level	delayed deliveries	9	delayed deliveries	7	possible average detection	6	**378**	Shipyard support	9	3	6	**162**	**RPN too high**
	low efficiency of mix production system	7	technical problems	7	possible full detection	3	**147**	research	7	3	3	63	

Intensity of generated threat *I*	Probability of occurrence *P*	Probability of detection *D*
1: Almost imperceptible	1: Improbable	1: ideal detection $D_{\%}\cong 100\%$
2-3: Small burden on the customer	2-3: Very little probable	2-5: full detection ($100\%>D_{\%}\geq 99.7\%$)
4-6: Moderate impact	4-6: Small probability	6-8: possible aver. detection ($99.7\%>D_{\%}\geq 98\%$)
7-8: Significant impact	7-8: Moderate probability	9: incomplete detection ($98\%>D_{\%}\geq 90\%$)
9-10: Very significant impact	9-10: High probability	10: lack of detection $D_{\%}\cong 0\%$

RPN **(Risk Priority Number) - Critical value of relative risk priority number *RPN*>100**

Tab. 6 contd.

Risk analysis for the requirements set in relation to the modernisation of hydrogen incinerators .

Type of problem/ problem situation	Effect of risk materialisation	Impact intensity upon risk materialisation	Probable cause of risk materialisation	Probability of risk materialisation	Possibility of detection of risk materialisation	Probability of risk materialisation	*RPN*	Applied countermeasures for risk materialisation	Corrected *RPN*				
		I		*P*		*D*	*RPN=I×P×D*		*I*	*P*	*D*	*RPN*	
Assurance of proper efficiency level	low efficiency of catalysis	9	wrong catalyst	4	possible full detection	2	72	research	9	2	2	36	
Assurance of proper reliability level	lack of a suitable mix	9	problems with equipment construction	4	possible full detection	2	72	research	9	2	2	36	
	bad market identification	9	knowledge gap	3	possible incomplete detection	9	**243**	Shipyard support	9	2	9	**162**	**RPN too high**
	unpunctual purchases	6	oversights	3	possible incomplete detection	7	**126**	Shipyard support	6	2	7	84	
Redundancy minimisation	hydrogen threat	9	poor component operation	4	possible average detection	6	**216**	research	9	2	6	**108**	**RPN too high**
	excessive purchases	4	poor identification of needs	4	possible average detection	6	96	acceptance	4	4	6	96	

Intensity of generated threat *I*	Probability of occurrence *P*	Probability of detection *D*
1:Almost imperceptible	1: Nieprawdopodobne	1: idealna detekcja $D_{\%} \cong 100\%$
2-3: Insignificant burden on the customer	2-3: Very little probable	2-5: full detection ($100\% > D_{\%} \geq 99.7\%$)
4-6: Moderate impact	4-6: Small probability	6-8: possible aver. detection ($99.7\% > D_{\%} \geq 98\%$)
7-8: Significant impact	7-8: Moderate probability	9: incomplete detection ($98\% > D_{\%} \geq 90\%$)
9-10: Very significant impact	9-10: High probability	10: lack of detection $D_{\%} \cong 0\%$

RPN **(Risk Priority Number) - Critical value of relative risk priority number *RPN* >100**

The risk and threat concepts are not used interchangeably here. The integral of the function of risk from the moment $t = 0$ until t defines here the hazard of risk materialisation.

In the considered process of modernisation of the hydrogen incinerators, 8 threats have been initially identified – tab. 6:

- obtaining an explosive mixture,
- incorrect market identification,
- delay of deliveries,
- excessive deliveries,
- lack of possibility of obtaining a catalyst,
- low efficiency of the catalytic process,
- failure to adapt the catalyst to the incinerator,
- failure to obtain air-hydrogen mix generating system or its inadequate efficiency,

The explosive composition of the air-hydrogen mixture may be due to many probable causes:

- inaptness of the measurement system,
- disturbances in the hydrogen and air flow,
- bad conditions for mixing hydrogen with air,
- poor operation of the components of the test stations or hydrogen incinerator.

The exact description of the analysis is omitted here due to the fact that the way it is carried out is similar to preliminary risk analysis described above. Its precise description can be found in the compact publication devoted to this issue [2].

The analysis revealed two key types of risk whose materialisation will be particularly severe in the process of project implementation – tab. 6. These include:

- danger of hydrogen explosion,
- lack of good market identification and timely delivery of catalyst and other materials.

The latter is critical for project implementation.

OPERATIONAL DEFINITIONS FOR PRODUCTS

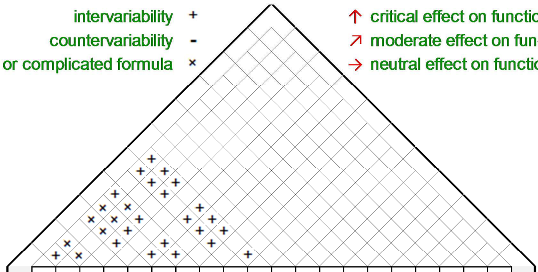
There are 8 key intermediary products for the process of modernisation of the hydrogen incinerators– fig. 5. The hierarchy of product functionality was derived from their ranking, determined in the course of quality planning – fig. 4:

1: $0 \leq Ranking < 360$
2: $360 \leq Ranking < 720$
3: $720 \leq Ranking < 1080$
4: $1080 \leq Ranking < 1440$
5: $1440 \leq Ranking \leq 1800$

Quality Function Deployment
Product Planning
Working principles of intermediate products required in the modernisation of hydrogen incinerators $PD-3A$

intervariability +
countervariability -
undertermined effect or complicated formula ×

↑ critical effect on functionality
↗ moderate effect on functionality
→ neutral effect on functionality



Characterisation of intermediate products

	Product functionality Critical to Quality (CTQ)	←score 1-5	hydrogen H2 concentration measurement system	incinerator parameters measurement system	flow measurement system		hydrogen H2 dosage system	air supply system	gas mixing system		Catalyst tests station	Delivery acceptance tests station	Maximum value
			↑	↗	↑		↑	↗	↑		↑	↑	
	Links between product and customer requirements (9-high; 3-moderate; 1-low; 0-no link)												
Informational	accuracy/probity	4	9	3	9		9	9	9		9	9	9
	currency	2	1	1	1		1	1	1		1	1	9
	adequacy	5	3	9	3		9	9	9		9	9	9
Technical	compatibility	2	9	3	9		9	9	9		9	9	9
	maintenance freeness	1	1	3	1		3	1	3		3	3	9
	efficiency	2	9	3	3		9	9	9		3	3	9
	reliability	5	9	9	9		9	9	9		9	9	9
Supporting	experience & SOP	2	9		9		9	1	1		3	3	9
	redundancy	1	1	1	1		1	1	1		1	1	9
	Intermediate products hierarchy		154	120	142		186	168	170		162	162	216
	Methods of realisation/target values of requirements for intermediate products		pellistor explosimeter	electronic temperature measurement	rotameter		continuous dosage system	pump	pipe mixer		regeneration-based system	shipboard system	Maximum value
	Indicator of difficulty in obtaining intermediate products (scale 1-5)		1	1	1		2	1	2		2	1	5
	Intermediate products ranking		154	120	142		372	168	340		324	162	1080

Competition products ranking - benchmarking → (1, 2, 3, 4, 5)

1: $0 \le Ranking < 216$
2: $216 \le Ranking < 432$
3: $432 \le Ranking < 648$
4: $648 \le Ranking < 864$
5: $864 \le Ranking \le 1080$

Fig. 5 The selection of working principles of basic products enabling the fulfilment of quality requirements CTQ for the process of modernisation of hydrogen incinerators.

The definitions of systems, that constitute products in the process of the modernisation of the hydrogen incinerators, have been partially provided during the analysis of critical quality requirements CTQ. They will be conclusively established with respect to the methods of handling or principles of operation of intermediate products used for:

- the measurement of hydrogen content – it was decided to use pellistor explosives[25],
- temperature measurement after each of the four catalyst beds,
- rotametric measurement of air and hydrogen flow,
- dosage of hydrogen flow,
- air dosage,
- mixing hydrogen with air,
- catalyst tests which at the maximum level should be equivalent with those performed at the delivery acceptance station.

QUALITY REQUIREMENTS FOR PRODUCTS

The quality requirements CTQ for intermediate products ensuring performance of the modernisation of the hydrogen incinerators have been specified:

- The pellistor system for measuring hydrogen content in air should ensure the coverage of hydrogen content C_{H_2} up to the lower explosion limit $C_{H_2}=[0;4]\%_v$ with an accuracy guaranteeing an occurrence of absolute error at the level of $\Delta C_{H_2} \lesssim 0{,}2\ \%_v$. Due to safety reasons, the measurement system of hydrogen content should exhibit a short response time t to threshold triggers $t<1$ s. The response time τ should not exceed $\tau \leq 2$ s.
- The multipoint temperature monitoring system within the range $t \in [0;300]$°C is performed with an accuracy expressed with an absolute error at the level $\Delta t \leq 5$°C. It will be used in temperature measurements after each of the four catalyst beds. This system is independent of the integral protection system with thermostats: it turns on the heater at approx. 40°C, a green control light signalling the heating process is in operation, and shuts off the current flow to the incinerator at a temperature of approx. 70°C.
- The air and hydrogen flow measurement system consisting of a rotameter set. In the case of the air-hydrogen mixture the flow will be measured with an air rotameter without taking into account the contained hydrogen. It should guarantee measurement of the air flow to the level of $\dot{V}_0 \in [0;\ 150]\ m^3 \cdot h^{-1} \triangleq [0;\ 2500]\ dm^3 \cdot min^{-1}$ in accordance with the specified accuracy. Similarly, the measurement of the flow of pure air will be protected with the same rotameters. The measurement of pure hydrogen flow will be carried out with a rotameter calibrated to air, this reading then being converted to indicate hydrogen flow. A rotameter, or a rotameter set, should ensure measurement of the hydrogen flow within the range of the measured volumetric hydrogen flux $\dot{V}_{H_2} \in [0;\ 4{,}5]\ m^3 \cdot h^{-1} \triangleq [0;\ 75]\ dm^3 \cdot min^{-1}$ with the resulting accuracy of the performed measurements.
- Hydrogen flow metering system, consisting of a reducer and the associated nozzle, operating in supercritical flows, will ensure the regulation of hydrogen flow after the determination of its function depending on the nozzle supply pressure. The nozzle will further limit the flow of hydrogen in the case of reducer failure.
- The air supply system will be carried out with the use of a fan. Initial tests will be performed with the use of a fan belonging to the *Academy*; this prototype would normally be utilised in the air supply system of life preservation systems. The remaining trials will be performed with the use of a marine fan in the suction system for the air-hydrogen mixture.
- Mixing of hydrogen and air flows will be carried out in a tubular reactor. In the course of these experimental works, it will be necessary to determine the length of the reactor as well as which material should be used for its content.
- If possible, the catalyst testing station should be identical to the station for conducting delivery acceptance tests. It should consist of hydrogen supply systems, air suction fittings composed of shipboard system components, the hydrogen incinerator with its automatics, hydrogen content monitoring system before and after the incinerator and temperature monitoring in the incinerator at each catalyst bed.

INTERMEDIATE PRODUCT HIERARCHY

It has been previously determined that nearly all of the intermediate products have a key impact on the functionality of the final product, i.e. the modernised set of hydrogen incinerators:

- hydrogen concentration measurement system,
- flow rate measurement system,
- hydrogen dosage system,
- gas mixing system,
- catalyst test station,
- delivery acceptance tests station.

The components which have a moderate impact on the functionality of the final product include:

- temperature measurement system after the incinerator beds,
- air flow supply system.

A system consisting of a multi-point temperature measurement device situated after the incinerator beds forms an additional product. It appears from the experience already gained, a lack of a cooling system for the incinerators can cause their thermal destruction.

Presumably the designers assumed that a large flow of hydrogen is generated only at the beginning of the ventilation process in the battery compartments. This may cause a temporary rise in temperature, however the subsequent ascent of heat along with the ventilation air is so considerable that there might even be a need to heat the bed.

The airflow system is less relevant for the modernisation of hydrogen incinerators as long as it does not interfere with the established compositions of the hydrogen-air mixtures being fed.

Relationships between intermediate products

Many of intermediate products reveal close links as most of them will be part of the catalyst and delivery acceptance tests stations.

The hydrogen measurement system is closely linked to the temperature measurement system of the incinerator as both of them will be connected to a single computer programme for data collection and *on-line* result visualisation. For the same reason, the hydrogen measurement system is linked by the interchangeable relationship between gas mixing, catalyst and delivery acceptance tests. It constitutes a protection for these systems against the formation of an explosive mixture, thus the measurements of hydrogen content in the flow is the basis for experiment safety.

The temperature measurement system of the hydrogen incinerator is only associated with stations for the catalyst and delivery acceptance tests.

The flow rate measurement system is not only important for the stations for catalyst and delivery acceptance tests, but also for the hydrogen dosage system, air supply and mixing systems. This is due to the necessity of conducting tests of the functionality of these systems implemented under rotametric control.

The hydrogen dosage system, in addition to the previously discussed links, along with the air supply and mixing systems, is strongly linked to the stations of catalyst and delivery acceptance tests of the hydrogen incinerators.

All active links are interchangeabilities, i.e. their changes occur in the same direction.

The ranking of products offered by the competition is not included as the *Academy* does not specialise in the area of catalysis reactions and such data are not collected, whereas the search for such data due to limited project implementation time and practical lack of competition would not be purposeful.

Difficulties in ensuring the quality of intermediate products

The preliminary analysis determined the ranking of importance of the intermediate products, highlighting the three most important ones (fig. 5):

- hydrogen dosage system,
- mixing system,
- air flow supply system.

It may seem strange that the safety-critical system of monitoring hydrogen content is at the top of this ranking. However, from the point of view of the *Academy*, the possessed competences within the measuring technique and construction of computer monitoring systems have allowed us to lower the ranking position of this issue, without losing sight of the key role of systems monitoring the hydrogen content and working temperatures of the bed.

After consideration of the relative index of difficulty in obtaining intermediate products, their ranking changed:

- hydrogen dosage system,
- mixing system,
- catalyst tests station,

In fact, the final ranking of importance of intermediate products is concentrated in a single consolidated testing station. This result is consistent with the impression that the most important intermediate product will be the test station as it contains all key intermediate products and in its modified version it forms a delivery acceptance tests station. The modification of the station will consist solely in the replacement of the pumping system by the dedicated shipboard fan and the cessation of additional temperature measurements.

The replacement of the installation with a typically marine one will potentially remove the need to carry out delivery acceptance tests on board the ship, where their performance involves an escalation of the risk of a technical disaster.

Tab. 7

Risk analysis in relation to intermediate products in the modernisation of $PD-3A$ hydrogen incinerators.

Type of problem/ problem situation	Effect of risk materialisation	Impact intensity upon risk materialisation	Probable cause of risk materalisation	Probability of risk materalisation	Possibility of detection of risk materalisation	Probability of detection of risk materialisation	*RPN*	Applied countermeasures for risk materialisation	Corrected *RPN*				
		I		*P*		*D*	*RPN=I×P×D*		*I*	*P*	*D*	*RPN*	
hydrogen concentration measurement system	production of an explosive mix	9	malfunctioning measurement system	4	incomplete detection	9	**324**	long-term implementation research	9	2	9	**162**	**RPN too high**
		9	lack of flow through analysers	7	incomplete detection	9	**567**	application of rotametric control	9	7	1	63	
		9	incorrect signal connection	6	possible average detection	6	**324**	research & SOP	9	2	5	90	
		9	lack of sufficient precision	3	possible average detection	7	**189**	metrological control	9	2	2	36	
incinerator parameters measurement system	overheating	4	long-term combustion of large hydrogen quantities	6	possible full detection	4	96	temperature measurements & SOP	4	4	4	64	
flow measurement system	wrong measurements	7	miscalculations or leakages	8	possible full detection	5	**280**	SOP	7	2	5	70	

Intensity of generated threat *I*	Probability of occurrence *P*	Probability of detection *D*
1:Almost imperceptible	1: Improbable	1: ideal detection $D_{\%}\cong 100\%$
2-3: Insignificant burder on the customer	2-3: Very little probable	2-5: full detection ($100\%>D_{\%}\geq 99.7\%$)
4-6: Moderate impact	4-6: Small probability	6-8: possible aver. detection ($99.7\%>D_{\%}\geq 98\%$)
7-8: Significant impact	7-8: Moderate probability	9: incomplete detection ($98\%>D_{\%}\geq 90\%$)
9-10: Very significant impact	9-10: High probability	10: lack of detection $D_{\%}\cong 0\%$

Tab. 7 contd.

Risk analysis in relation to intermediate products in the modernisation of $PD-3A$ hydrogen incinerators.

Type of problem/ problem situation	Effect of risk materialisation	Impact intensity upon risk materialisation I	Probable cause of risk materialisation	Probability of risk materialisation P	Possibility of detection of risk materialisation	Probability of detection of risk materialisation D	RPN $RPN=I×P×D$	Applied countermeasures for risk materialisation	Corrected RPN I	P	D	RPN
hydrogen dosage system	production of an explosive mix	9	damage	3	possible full detection	5	**135**	implementation research	9	3	3	81
air flow feeding system	production of an explosive mix	9	choking	7	possible ideal detection	1	63	implementation research	9	4	1	36
mixing system	production of an explosive mix	9	insufficient hydrogen expansion	9	possible full detection	2	**162**	implementation research	9	3	2	54
catalyst tests station	incinerator destruction	6	sudden increase of working temperature	7	possible full detection	3	**126**	application of temperature measurements	6	2	3	36
delivery acceptance tests station	production of an explosive mix	9	bad mixing conditions	8	possible full detection	2	**144**	measurements	9	8	1	72
delivery acceptance tests station	lack of acceptance of works	10	erroneous measurements	3	possible full detection	3	90	SOP	10	3	2	60

Intensity of generated threat I	Probability of occurrence P	Probability of detection D
1:Almost imperceptible	1: Improbable	1: ideal detection $D_{\%}\cong100\%$
2-3: Insignificant burden on the customer	2-3: Very little probable	2-5: full detection $(100\%>D_{\%}\geq99.7\%)$
4-6: Moderate impact	4-6: Small probability	6-8: possible aver. detection $(99.7\%>D_{\%}\geq98\%)$
7-8: Significant impact	7-8: Moderate probability	9: incomplete detection $(98\%>D_{\%}\geq90\%)$
9-10: Very significant impact	9-10:High probability	10: lack of detection $D_{\%}\cong0\%$

RPN **(Risk Priority Number) - Critical value of relative risk priority number *RPN*>100**

RISK ANALYSIS FOR PRODUCTS

After analysing the quality requirements for partial products, it is sensible to perform an in-depth hazard analysis using the $FMEA$ method. The discussed process allowed initial diagnosis of 5 threats presented in tab. 7:

- production of an explosive mixture,
- overheating,
- erroneous measurements,
- destruction of the incinerator,
- non-acceptance of works.

The exact description of the analysis is omitted here due to the fact that the way it is carried out is similar to preliminary risk analysis described above. Its precise description can be found in the compact publication devoted to this issue [2].

OPERATIONAL DEFINITIONS AND QUALITY REQUIREMENTS FOR PROCESSES

For the defined 6 key processes leading to the obtainment of both intermediate and final products compliant with the quality requirements CTQ for the process of modernisation of the hydrogen incinerators $PD-3A$ – see fig. 6. Their definitions are provided below:

- the flow of supplied hydrogen should be contained within the range $\dot{V}_{H_2} \in$ $\in [0;\ 4{,}5] m^3 \cdot h^{-1} \triangleq [0;\ 75] dm^3 \cdot min^{-1}$ with an accuracy resulting from rotameters available on the open market,
- the flow of supplied air should be within the limits $\dot{V}_0 \in [0;\ 150] m^3 \cdot h^{-1} \triangleq [0;\ 2500] dm^3 \cdot min^{-1}$ with an accuracy resulting from rotameters available on the open market,
- mixing should be quantitative without observable gas stratification,
- catalyst tests should ensure a minimum tenfold reduction of hydrogen concentration with regard to its maximum concentrations in the air-hydrogen mixture being fed,
- modernisation of the hydrogen incinerators should ensure a minimum tenfold reduction of hydrogen concentration with regard to its maximum concentrations in the air-hydrogen mixture,
- during delivery acceptance tests on hydrogen incinerators a minimum tenfold reduction of hydrogen concentration should be ensured with regard to its maximum content in the air-hydrogen mixture.

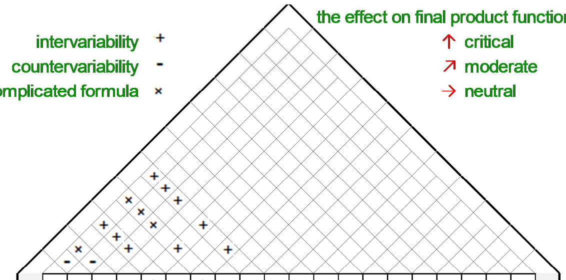
For operational purposes, the values of the effects of the implemented processes should be monitored by measuring:

- hydrogen content before the incinerator,
- hydrogen content after the incinerator.

Quality Function Deployment
Process Planning
processes needed in planning modernisation of hydrogen incinerators $PD-3A$

intervariability +
countervariability -
undetermined impact or complicated formula ×

the effect on final product functionality
↑ critical
↗ moderate
→ neutral



	Basic products	←score 1-5	hydrogen dosage	air dosage	mixing		catalyst tests		incinerator modernisation		delivery acceptance tests	Maximum value	Competition products ranking - benchmarking 1 / 2 / 3 / 4 / 5
			↗	↗	↗		↑		↑		→		
			Main operations in the process of product production										
			Links between requirements defined for processes and intermediate products (9-high; 3-moderate; 1-low; 0-no link)										
Logistics	hydrogen H2 concentration measurement system	1	1	1	3		9		9		9	9	
	incinerator parameters measurement system	1	3	3	9		3		9		3	9	
	flow measurement system	1	3	3	9		3		9		3	9	
Production	hydrogen H2 dosing system	2	9				3		9			9	
	air supply system	1	9	9	1		3		9		3	9	
	gas mixing system	2	9	9	3		1		9		9	9	
Quality assurance	Catalyst tests station	2		1	1				9		9	9	
	delivery acceptance tests station	1	3	3	1		9		9		9	9	
	Product parameters ranking		55	39	31		35		99		63	99	
	Target requirement value for product		$\dot{V}_{H_2} \in [0; 4{,}5] m^3 \cdot h^{-1}$	$\dot{V}_o \in [0; 150] m^3 \cdot h^{-1}$	full 100%		>10 x H2 reduction		≥10 × H2 concen. reduction		≥10 × H2 concen. reduction		
	Indicators of performance difficulty (scale 1-5)		1	1	2		3		1		2	5	
	Critical parameters ranking		55	39	62		105		99		126	495	

Fig. 6 Basic sub-processes for the production of intermediate products meeting the quality requirements CTQ of the modernisation process on hydrogen incinerators $PD-3A$.

The following processes are of key importance for the modernisation process on hydrogen incinerators:

- catalyst tests,
- performance of incinerator modernisation.

Since the modernisation involves solely the replacement of the catalyst, it can be assumed that the above processes can be regarded as one, being related to the right choice of catalyst.

The following processes have a moderate impact on the functionality of the hydrogen incinerators after the modernisation:

- hydrogen dosage,
- air dosage,
- mixing.

These are processes that lead to intermediate products enabling the tests to be carried out and, consequently, selection of the right catalyst.

The process of carrying out delivery acceptance tests has a neutral impact on the functionality of hydrogen incinerators. However, it has an influence on the confirmation of the incinerators' functionality after the modernisation and is essential for the acceptance of the scope of the implemented project. Therefore, the process of carrying out delivery acceptance tests cannot be discounted on the basis presented here.

THE RELATIONSHIP BETWEEN PROCESSES

The QFD analysis for the processes required in the project has shown that many of them are interdependent[26]. This is understandable as the majority of processes are conducted in order to design, build and test the components of the station meant for carrying out catalyst and delivery acceptance tests.

By ensuring perfect mixing, increasing the flow of supplied hydrogen with a stabilised flow of supplied air we can observe an increase in hydrogen content in the mixture. Conversely, by raising the flow of supplied air with a stabilised flow of supplied hydrogen we can observe a reduction of hydrogen content. Therefore, it follows that in the case of a stabilised hydrogen content in the air-hydrogen mixture, an increase in the flow of supplied hydrogen produces the same effect as a reduction of the supplied flow of air, and vice versa. Therefore, in fig.6 it was determined that the sizes of the hydrogen and air flows are counter variable.

The effect of hydrogen dosing on the mixing process in the range of low hydrogen concentrations is difficult to theoretically determine prior to the tests commencement. Due to the high volatility of hydrogen, it can be assumed that ideal hydrogen / air miscibility exists within the range of small concentrations.

The ability to regulate hydrogen dosage can have a significant impact on catalyst and delivery acceptance tests, whereas the impact of such rangeability on the process of modernisation of the hydrogen incinerators cannot be determined.

Similar interactions to those observed with regard to hydrogen dosage are observed for air dispensing. In addition to the previously discussed interactions with hydrogen and air dispensing processes, the mixing process has a significant impact on the safety and effectiveness of the catalyst and delivery acceptance tests. However, it is not easy to diagnose its impact on the modernisation process on the incinerators which is only indirect when it comes to its impact on the catalyst testing process.

In addition to previously diagnosed interactions, the catalyst testing process exerts a direct impact on the process of modernisation of the incinerators. As with the final tests, it has an overwhelming impact on an unquestionable acceptance of performance of the project scope and, on this basis, the final approval of the modernisation of the hydrogen incinerators.

QUALITY REQUIREMENTS FOR PROCESSES

The results presented in fig. 5, in relation to the conducted analysis of the basic products that will allow achievement of the CTQ requirements for the modernisation process on the hydrogen incinerators, together with the results presented in tab. 6 of a risk analysis carried out with the use of the $FMEA$ method for the main risks related to the intermediate products, ensures the implementation of the modernisation process, and constitute the basis for further analysis by means of the QFD method of significant processes aimed at obtaining such necessary products and ensuring quality requirements CTQ during the implementation of the project.

The scale of impact of particular quality requirements on products assuring the fulfilment of those quality requirements CTQ were transferred from the analysis shown in fig. 6, in proportion to the score obtained in the ranking concluding the QFD analysis, according to the following system:

1: $0 \leq Ranking < 216$
2: $216 \leq Ranking < 432$
3: $432 \leq Ranking < 648$
4: $648 \leq Ranking < 864$
5: $864 \leq Ranking \leq 1080$

The determination of the strength of interdependencies between the requirements for intermediate processes and products according to the scale:

9: high
3: moderate
1: low
0: no interdependency

presented in fig. 6. The following have been identified as the three most important processes for obtaining intermediate products that ensure meeting the quality requirements CTQ that affect the process of project implementation:

- hydrogen dosage,
- incinerator modernisation,
- carrying out delivery acceptance tests.

However, after taking into account the indicators of difficulty in implementing particular processes, the process ranking was re-evaluated:

- catalyst tests,
- incinerator modernisation,
- carrying out delivery acceptance tests.

The result is understandable as hydrogen dosage is undoubtedly a part of the catalyst testing process, having a powerful impact on it. The modernisation of incinerators and performance of delivery acceptance tests is a condition for the positive completion of the project.

RECORDS

The return to the starting point after carrying out the QFD analysis for the processes is a sign of a well-conducted analysis process and subsequent synthesis of the technical feasibility study of the project. It is reasonable to assume, that by analysing all the phases of the process of incinerator modernisation, it has been possible to avoid omitting any significant risk connected with its implementation. After risk recapitalisation, it will be possible to try to minimise its impact, mainly by raising certain reservations while signing the contract for project implementation.

Such wide knowledge of all types of risk constitutes a good starting point for negotiating contractual terms. It also gives one the opportunity to consider the transfer of certain types of risk onto the project initiator or insurer. Transparent negotiations with the project initiator on the basis of the conducted analysis, builds professional ties based on trust to the business partner.

MEASURING SYSTEM

The measurement system consisted of two $pellistor$ sensors: $POLYTRON\ 2\ XP$. Sensors were connected with the use of analog-to-digital converters with dedicated software. The flow of analysed gas through the sensors was regulated with electronic flowmeters connected in series with a rotameter as a flow indicator.

The plausibility check of the measurement system used in the project is presented in the compact study [2].

DEFECTS

The defects during the initial testing will be understood as any violation of the requirements for the products and sub-processes that must be carried out to complete the process of modernisation of the hydrogen incinerators.

The most important defect is related to the carrying out of acceptance tests for which the hydrogen incinerators should ensure at least a tenfold reduction in hydrogen concentration in relation to maximum values of its content in the hydrogen-air mixture.

CONCLUSIONS

The chapter defined critical quality requirements CTQ for the products and processes that support the process of modernisation of the hydrogen incinerators.

The following 9 quality requirements were defined as critical CTQ: probity/accuracy, timeliness, adequacy, compatibility, low maintenance, efficiency, reliability, experience and SOP, and redundancy. By way of analysis, QFD ranking of the three most important quality requirements was performed CTQ: probity/accuracy, adequacy, reliability.

8 key intermediate products in the form of systems were determined: measurement of hydrogen content in the air, measurement of incinerator parameters, air and hydrogen flow measurement, hydrogen flow dosage, air supply, hydrogen and air mixing, performance of stations for acceptance tests and trials. It was determined that the following partial products are crucial for the functionality of the final product: hydrogen concentration measurement system, flow measurement system, hydrogen dosage system, gas mixing system, catalyst testing station, acceptance testing station. The following systems have a moderate effect on the functionality of the final product: incinerator temperature measurement, air stream supply.

Six key processes have been identified in ensuring intermediate and final products which meet the critical quality requirements CTQ of the process of modernisation of the hydrogen incinerators: measurement of hydrogen dosage, measurement of air dosage, the mixing process, catalyst tests, modernisation of the incinerators, delivery acceptance tests. It was determined that operational objectives should encompass careful monitoring of values of implemented processes through measurement of hydrogen content before and after the incinerator. The following processes are of key importance for the modernisation process on hydrogen incinerators: catalyst tests and carrying out of incinerator modernisation. Since the modernisation involves only the replacement of the catalyst the above processes can be regarded as one, related to the right choice of the catalyst.

The following processes have a moderate impact on the functionality of hydrogen incinerators after the modernisation: hydrogen dosing, air dosing and mixing of hydrogen with air. These are processes that lead to intermediate products enabling the tests to be carried out and, consequently, to select the right catalyst. The process of carrying out delivery acceptance tests has a neutral impact on the functionality of the hydrogen incinerators. However, it has an impact on determining their functionality following the modernisation and is essential in the process of acceptance of the final results of the project, hence the process of carrying out delivery acceptance tests can not be underestimated.

For critical quality requirements CTQ for products and processes, a risk analysis was performed using the $FMEA$ method.

Critical measurable quality requirements CTQ have been defined for basic and auxiliary processes and products. A plausibility study of the measurement process for the selected type of analysers was performed in relation to key quality requirements CTQ for the determination of hydrogen content. Such a study was not performed in relation to temperature and pressure measurements as the role of these measurements in the project is only demonstrative and has no key impact on critical quality requirements CTQ. Based on the capitalisation of knowledge in the construction and use of measurement systems in different research, it was found that their reliability was sufficient to meet project objectives and ensure critical quality requirements CTQ.

It has been found that the $pellistor$ analyser $POLYTRON\ 2\ XP\ Ex$, with the provided measurement network and dedicated software, meets critical quality requirements CTQ. The main response of the metering system was determined in the performance of delivery acceptance tests in the form of defect descriptions. A data collection plan was established, and the efficiency standards defined for the measurement process as being at least a tenfold reduction in the hydrogen concentration in relation to its maximum content in the air-hydrogen mixture.

The process map was re-analysed, without any modifications being introduced. There was no in-depth analysis based on the process map, as the activities undertaken in the project will not be repeated, being only a one-time process in the entire incinerator modernisation process[27].

It is also not anticipated that systematic catalysts tests will be commissioned, hence the test stations will be dismantled and the related SOP will be used in different research works. The main and selected auxiliary system response[28] limits for the measured values were specified. Metrological tests and $R\&R$ analysis of the efficiency of the measurement system for monitoring the main system responses were conducted. The collected data will also be used in the next phases of the project.

FINAL CONCLUSIONS

The presented series of articles constitutes a case study for a high-risk project involving a budget limitation and a constrained implementation time for a little recognised scope and a diagnosed knowledge gap. By necessity, such a project is carried out with a continuous compromise between the provision of a minimum quality level and balancing on the edge of performance of its full scope.

Undertaking high-risk projects should be based on the expected high reward for taking the risk or decent conditions for transferring a substantial part of the risk. At times such ventures result from a necessity, as in the case of a rescue operation, whether it involves saving lives or property.

The discussed project was undertaken for prestige reasons. Although such a decision is considered unreasonable from the point of view of project management theories, it is deeply rooted in the Slavic tradition. The final decision on project initiation was made due to the mediatory attitude of the project initiator.

In the order, the project initiator withdrew from the determination of contractual penalties and the need to reimburse the amounts spent on the project. However, in the absence of the expected effects, no remuneration for work was to be provided. This is an example of co-sharing of risks practised in $joint-venture$ undertakings or according to the $win-win$ model of negotiations. Such a weakening of the risk impact at the time of its materialisation causes that the project is possible to implement for prestige rather than economic reasons as in return for the reduction of the effects of materialised risk the bonus for the risk undertaken was also reduced.

The description of the implementation of the preliminary part of the project attempted in this article was intended to combine several tasks:

- demonstrate the progress of organisation in implementing the $DMAIC$ [29] approach in the implementation of the substantive part of the project
- popularise the scientific approach not only with regard to technical but also organisational modelling in order to rationally increase the appetite for risk

The previous articles of the series contain possibly the fullest technical description of the progress of the organisation in acquiring technical competences in the area of hydrogen combustion on a submarine.

Documentation of the $know-how$ acquired during project implementation constitutes a starting point for the capitalisation of knowledge in the organisation. It may not only be used by our successors, but is a reminder of the possibility of returning to seldom-exploited areas of knowledge and competences, as is the case related to the implementation of works concerned with the problem of catalysis by the $Naval\ Academy$.

In concord with the imposed recommendations, the $Academy$ is obligated to build a project management system based on $PRINCE$ 2™. This method, however, refers to the organisation of the project on the basis of the $DMAIC$ loop only with regard to the improvement of the project management system. The $DMAIC$ approach to the implementation and improvement of products and processes in the substantive part of the project is characteristic of the $Six-Sigma$ approach which is preferred here. The combination of management and scientific methods of project implementation into a single approach gives the possibility of developing the organisation by improving the quality of scientific works.

Obtaining of funding for scientific works in Poland has thus far been primarily based on the competition formula. With limited funds to finance science on the one hand and the increased demand to practice it in academic environments[30] on the other, there is a need to undertake more and more risky projects. Universities are forced to pursue such an activity by the industry, which in the present day has a decisive voice when it comes to financing application research. As a rule, the industry imposes strict conditions agreeing only to finance the implementation and rarely the developmental part, and most often refuses to finance industrial research, without which it is impossible for a school of higher education to become involved in project implementation.

In order to make the offer more attractive, aspiring researchers undertake the risk of increasing the scope of projects with a reduced budget. However, such a conduct seriously increases the risk of an unpunctual implementation of the scope of the project with an additional minimum quality of execution of processes and products. It may also lead to non-completion of the scope of the project and the need for reimbursement.

Of course, scientific groups should rationally increase their appetite for risk, which is not a problem as it is most often transferred onto the university. However, the unconcerned risk escalation in a high-budget project may completely ruin the university's finances and cause unemployment also among those research teams which had acted reasonably.

Risk balancing should be performed at the level of the university or its primary organisational unit, preferably at the level of the designated $Project\ Office$. The evaluation and approval for an aspiration to implement a particular project should be based on a feasibility study, whose basic part entangles the determination of mutual relations in the project: budget, scope, time and quality. The ability to quickly assess these relations will allow to convince external and internal stakeholders of the purposefulness of entrusting a given project to the team that legitimises its aspirations with the use of scientific methods of project assessment.

This publication may constitute a contradiction to the general opinion that performance of an evaluation of a project scope is unreasonable or even infeasible in the short period of time needed to reach a decision on project implementation. It may also constitute a didactic illustration of the interdependencies and the need to constantly build a balance between the following parts: scope, budget, time and quality in the project.

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[1] i.e. Strengths, Weaknesses, Opportunities, Threat;
[2] further results of this analysis have been consolidated in the answers to questions concerning the left side of tab. 3;
[3] a casual link –;
[4] i.e. Critical to Quality;
[5] at the time of our affiliation to the Warsaw Pact, the Academy worked on the replacement of supplies from capitalist countries with local deliveries or those from Comecon countries, hence the current situation is not particularly difficult for the engineers working at the Academy;
[6] i.e. Failure Mode and Effects Analysis;
[7] Product Division Structure;
[8] project structure determination, Work Breaking Structure;
[9] The FMEA method performs risk hierarchisation in relation to the probability and not severity of their impact, hence it often directs the actions towards minimisation of the less financially critical effects of risk materialisation and leaves those more significant as residual;
[10] attested hydrogen-air mixes were used with hydrogen content below the lower flammability level so that even their uncontrolled leakage caused a significant reduction in hydrogen content and eliminated the possibility of its explosion;
[11] the applied concepts are those of a risk and threat, the link between them should be understood in such a way that the integral of the risk function from the moment $t = 0$ until t determines the threat of risk materialisation;
[12] purchase and distribution of the significant quantities of hydrogen-air mixtures used here is technically troublesome and unjustified in economic terms;
[13] i.e. Risk Priority Number;
[14] i.e. Suppliers;
[15] the Delhi method is based on knowledge, experience and opinions of experts in a particular area;
[16] i.e. Focus Inputs Process Outputs Customers;
[17] Demonstration of a system prototype or model, or a technology subsystem in conditions approximated to actual. This means that a representative system model or prototype has been tested in conditions similar to real operational conditions. This level represents a major step forward in the demonstrated technological readiness. This includes prototype testing in laboratory conditions simulating actual or operating conditions;
[18] i.e. Standard Operational Procedures;
[19] i.e. Quality Function Deployment;
[20] diagnosis is understood here as a formulation of conclusions concerning the condition of the system on the basis of tests on the processes, occurring within it or their effects, usually allowing to formulate prospective recommendations;
[21] probity, relevance, adequacy, predictability, punctuality, speed, susceptibility, reliability, redundancy;
[22] technique is understood here as purposeful, rational, theory-based manner of conducting works in the discussed area;
[23] knowledge on processing raw materials into consumer goods in a purposeful and economic manner;
[24] indirect;
[25] Pellistors (combination of words pellet and resistor) are porous ceramic elements containing a particular catalytic material with an embedded platinum wire ensuring the flow of electrical current which heats the whole component up to the temperature of several hundred degrees Celsius. If as a result of catalytic hydrogen oxidation the temperature increases, the wire resistance should proportionally increase. Changes in resistance constitute an analytical signal;
[26] numerous interactions are expected;
[27] undertaking of attempts to improve the process of incinerator modernisation and catalyst tests would undoubtedly involve …suffering unnecessary financial loss in the absence of any anticipated orders for this product;
[28] key for the project implementation;
[29] i.e. Define-Measure-Analyse-Improve-Control;
[30] revealed in the parametrisation of basic scientific units.