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FLAMMABILITY EVALUATION OF FLUIDS. A SURVEY OF LITERATURE AND STANDARDS

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Abstract

The fires and their consequences caused by them are a serious danger to many industrial branches where there are sufficiently high temperatures in operation to be a source of ignition and maintenance of combustion. These sources of ignition may result from temperatures required during the technological process, including steel and glass production, oil refining, casting and forging, or as a result of friction generated among machine components, as an inevitable by-product of normal operation.

Taking into account the consulted literature and standards, it can be stated that no test can provide a complete characterization of the fire resistance of a hydraulic fluid. The designer and the responsible with work security have to promote a set of appropriate tests for avoiding ascertainable hazards for a particular application.

Keywords: fluid flammability, test, fire resistance of fluid

1. RISK OF FIRE IN INDUSTRIAL ACTIVITIES

Fires and their consequences caused by them are a serious danger to many industrial branches where there are sufficiently high temperatures in operation to be a source of ignition and maintenance of combustion. These sources of ignition may result from temperatures required during technological process, including steel and glass production, oil refining, casting and forging, or as a result of friction generated among machine components, as an inevitable by-product of normal operation.

In the recent years, the environmental impact has expanded its traditional meaning to include other extensive concepts concerning the possibility of industrial accidents, which are capable of causing significant damage to people and the environment [1], [2], [3], [4]. This problem, which in the past has been mainly associated with the nuclear industry, now includes chemical, mining, oil and industry and trasnports and its safety. Among these, designers and users concern on fire events caused by material leakage, at or above their self-ignition temperature, or flash point or within their flammability limits.

Recent trends in hydraulics [5] may increase the likelihood of accidental fire. Machines have demanded higher speeds and loads, resulting higher operating temperatures. Hydraulic systems have been made smaller to reduce costs, thus requiring higher pressures in the system to maintain increased efficiency. Higher pressures, with higher working temperatures, will increase the probability that hydraulic fluids will "escape" from the hydraulic system and come into contact with an ignition source. Smaller fluid reservoirs in the modern designed systems also mean a higher frequency of fluid flow throughout the system, resulting in an increase in fluid temperature due to pumping and mechanical shearing process, which can increase hydraulic fluid degradation and the possibility of operating the equipment with sub-standard hydraulic fluids and potentially less fire resistant, at start the fluid being acceptable.

One of the industries that initiated the lead to industrial fire safety, the mining (coal) industry is still one of the most dangerous industries in some areas of the globe. China, in official figures, recorded the peak of accidental deaths of thousands among coal miners in 1998 and 1999 [6].

Accidents in the chemical industry almost always result from the loss of hydraulic fluid [15]. Deposits of liquid may be sprayed to form an aerosol. These drops have the ability to spread over an area larger than the liquid itself. A problem with great potential for danger is that which arises when a liquid fuel is atomized. There is a misconception, quite often found, that liquid fuels are safe when they are below their flash point, whereas, in fact, aerosols of liquid fuels at lower temperatures, far below their flash point, can be explosive as mixtures of vapors and air.

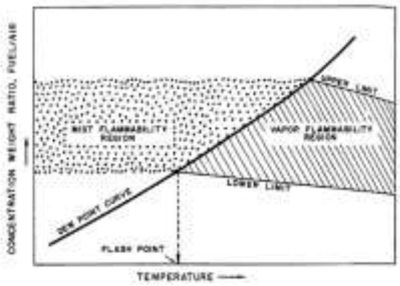

Fig. 1. Flammability diagram at constant pressure [8], [7]

Phillips [7] and Eichhorn [8] made a distinction between vapor flammability and aerosol flammability and acknowledged that aerosols can explode. Figure 1 presents a diagram proposed by Eichhorn, indicating that the flammability region of vapors is limited by thick lines, representing the upper and lower limit of vapor flammability. These limits are well known and are determined by standardized methods. The flammable area of the sprayed liquid located on the left side of the dew point curve, below the flash point, has been delimited by unclear boundaries, because the flammability limits of the aerosol are unknown and have not yet been established. Data on the upper and lower flammability limits of the vapor region are well established and are used as criteria in engineering design. However, due to the lack of data in the sprayed area, the flammability of the aerosol is generally neglected, sometimes with devastating consequences.

Statistics of [9] for the last 10 years revealed that 54 fires and explosions involving heat transfer fluids, cuased losses evaluated at 150 millioans US$. Any factory, stockspace, transport facilities have possible ignition sources, many of them not being cleary identified by stuff responsible of operators' security [15]. When the ignision source are identified, they should be eliminated Factory Mutual Engineering Corporation studied the ignition sources of more than 25000 fire (Fig. 2).

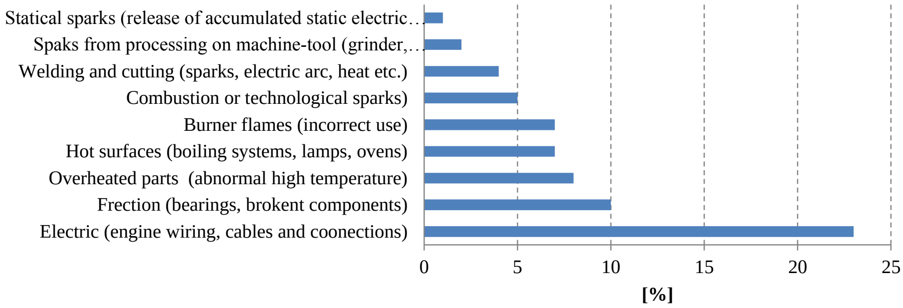

Fig. 2. Ignition sources for major fire [7]

Potential sources of ignition, such as sparks, electric arc, high surface temperatures, acoustic energy, optical radiation and electromagnetic waves have been identified in Council Directive 92/104/EEC [10] as potentially present in underground mines. A list, which is not considered complete, of possible situations in which these sources of ignition may occur includes: discharge of electrostatic electricity, eddy electrical current loss or discharges resulting from the incorrect operation of the power source equipment, which could cause overheating of surfaces or spark capable of causing ignition, moving surfaces or foreign bodies between the moving surfaces, determined, for example, by failure (breakage) of the mechanical parts, which leads to local overheating, high temperatures of the surfaces in internal combustion engines, braking systems, transmissions or exhaust fans, smoking or materials prohibited in some mines, risky zones in chemical and steel industry, existing fires caused by the ignition of other flammable materials.

During the preparation of the document HSE Approved Specifications for fire resistance and hygiene of the hydraulic fluids for use in machinery and equipment in mines [11], some fire hazards have been identified as being directly related to the use of hydraulic fluids underground and are in addition to the basic danger from the underground - the difficulty of access and exit, determined by the closed work areas. These fire hazards are: ignition of flammable vapors produced by hydraulic fluids, the ignition of the hydraulic fluids ejected from the hydrostatic and hydrodynamic systems, in the form of a spray jet, with the production of smoke, heat, flame and possibly toxic products, the ignition of a hydraulic fluid that flows from hydrostatic or hydrodynamic systems or is lost during transport on an absorbent material, such as lining (mines) on machines or in flammable dust and, consequently, the spread of fire along the absorbent material, the ignition of a fluid stream or a pool with smoke production, flame heat and possible toxic products, the ignition of the hydraulic fluids when their fire resistance was reduced by operation. Examples would be evaporation or separation [12]-[16].

2. FLAMMABILITY AND FIRE-RESISTANCE

A priori requirement for the development of fire-resistant fluids and the standards [33]-[40] that assess their performance is the ability to measure "fire resistance". This is a relative term. When referring to hydraulic fluids, it often means fire resistance as compared to mineral oils. This does not mean that the fluid is not flammable. All commercially available fluids will burn at a certain temperature, sufficiently high [17].

The measurement of fire resistance is a complicated subject, as resulting from publications and test methods. Although only three factors are required for combustion, air or oxygen, fuel and a source of ignition, there are other factors that affect these main aspects of liquid combustion, ease of ignition or ignition capacity and the persistence of combustion or flame propagation. For example, the physical form of fuel (solid, liquid or gas) and, if it is liquid, how it is present (in large or small drops or in large volumes), its volatility and stability to oxidation, temperature and if the process of chemical reactions is endotherm or exotherm. Similarly, the effects of the ignition source could be different, depending on the emitted energy or temperature, the contact time and the presence of free radicals that can catalyze the oxidation process. Due to the large number of variables involved in ignition and/or combustion, the easiest and most frequent solution was to simulate a specific set of conditions that are representative of the hazard considered.

Under these conditions, the development of test methods has focused on flammability [18]-[29]. In addition, it is necessary to evaluate the performance of fluids when absorbed in a substrate, simulating the effect of fluid leakage on insulation or other absorbent materials such as coal dust [78]. Under normal and abnormal conditions, volatile components, such as water, may be lost and the flammability of the fluid changes in time. The soaked wick procedure normally involves measuring the persistence of combustion and propagating the flame.

The wide variety of test methods has produced a diversity of definitions for fire resistance. Zinc [17] proposed to characterize a fire-resistant by properties as: the fluid must withstand ignition, the fluid should have the ability to aspirate the flame and prevent it from spreading when the ignition source is present and the fluid should self-extinguish when the source of the flame is removed. There is no single property or test for a fluid that can qualitatively quantify its fire resistance. This has led to the "simulated incident" approach whereby tests are designed to be a replica of the worst case scenario in typical applications where a fluid is used near a potential fire hazard. Fluids pass or fail these tests, and those that pass them are included in approval guides (or recommendations) or in a list of "qualified" fluids [5]. "Fire resistant" does not mean "fire protected" or flame retardant and that almost any fluid can burn under certain circumstances.

Selecting the right type of fluid for an industrial application requires consideration of several factors [5], [17], [30], [31], [32]: compatibility with the system, cost, lubrication, operating temperature, maintenance requirements, load capacity, operating pressure, problems regarding personnel health, safety and environmental protection, fire resistance.

3. TESTS FOR ASSESSING THE FIRE RESISTANCE OF FLUIDS

3.1. Particular aspects

Tests for establishing fire resistance properties are of two types [6], [17]: those dealing with the ignition and those for quantifying the consequences of the burning fluid. In 1996, "a recent evaluation revealed nearly fifty methods, all claiming to measure different aspects of the fire resistance of a fluid" [31]. The large number of tests that are available in the literature and standards can generally be classified according to four criteria: the property of fire resistance that is measured, the ignition source used in the test, the state of the fluid during the test and the test either simulates an accident condition or measures an intrinsic fluid property. There are several aspects of fire resistance and a test can measure one or more of them including: ease of ignition, releasing heat from combustion, spreading flame, self-extinguishing, smoke and combustion products etc. Almost all fire resistance tests ignite (or tend to ignite) the fluid in the test procedure. The ignition source is a distinct feature of the test method. Potential sources of ignition include: radiant heat; pilot flame, hot surface, electric arc. Fire resistance tests can also be classified by fluid status during the test. For example: spray; accumulation; imbibed substrate; flowing fluid. Finally, some tests are based on accident simulation (either explicit or implicit). Others measure a property of the fluid and are not based on the conditions of a particular type of accident.

The standards [33]-[41] included test methods that tried to reproduce the most common ways in which ignitions of fluids in the industry could occur. Spray flammability, tests on hot surface, and soaked wick tests measured the ability of the hydraulic fluid tested to maintain combustion after the ignition source was removed from contact with hydraulic fluid or hydraulic fluid impregnated material [30].

3.2. Spray ignition tests

One of the most common test methods used in industry and national standards to evaluate the relative fire resistance of hydraulic fluids was the spray flammability test, which measured the ability of the hydraulic fluid tested to maintain combustion after the ignition source was removed from the ignition source contact with the fluid. The lack of reproducibility and the inability to differentiate the types of hydraulic fluids have been two real criticisms of spray flammability tests [17], [30], [49].

There are three test methods, all of which involve trying to ignite a sprayed fluid jet under well-defined conditions and which are used to estimate the fire hazard caused by ignition of the sprayed fluid jet. All are detailed in [11] as methods 3.1.1, 3.1.2 and 3.1.3. Method 3.1.2 is identical to ISO 15029-1: 1999 [38], and method 3.1.3 is identical to ISO 15029-2 [39]. Both methods 3.1.3 and 3.1.2 give a criterion for passing or failing the test. The "Community of 6" test differs from that of Great Britain by the nozzle used to produce the jet, by details of the ignition procedure and the criteria for passing the test. In the "Community of 6" test, the passing / not passing criterion implies both the ignition of the fluid and the length of the flame produced by the ignition. In the UK test, the criterion is persistence of burning. Fluids that pass one of the tests do not necessarily pass the other.

The third test, (3.1.3) in [11], is the "stabilized flame heat release test" that try to harmonize the results from the other tests described above. A quantity of heat supplied by a flame from a pilot burner is used to ignite a well-defined, fluid spray stream, but in this case the ignition capacity of the fluid is measured by the amount of heat it releases. The temperature differences between the inlet air in the test enclosure and the exhaust gases are measured without discharge of fluid through the nozzle, and by spraying the fluid through the nozzle.

The difference in temperature is a measure by the heat released. An RI ignition factor is calculated based on the relationship between the temperature differences, that is, the heat released, when only the burner is lit, and when the fluid jet is ignited by the burner. Smoke production and flame length can be measured. In contrast to other methods, the stabilized flame heat release test quantifies the fire hazard, giving the user the opportunity to use the information generated by a risk estimation procedure and to choose an appropriate level of fire resistance for its application. The performances obtained by this test are not necessarily related to the performances obtained in the other two tests.

3.3. Ignition tests for fluid-soaked materials

BS EN ISO 14935: 1999 Determination of wick flame persistence of fire-resistant fluids [38] has been considered appropriate to measure the fire resistance of fluids when absorbed (soaked) in absorbent or flammable materials and the extent to which the fluid will propagate fire. The test is described in section 3.2.1 in [11], but also in the British mining specifications no. 570. Initially, this test was performed using asbestos chips, but it was replaced with aluminum-silicate strips. In this test, a flame is applied to a wick that has been soaked in the test fluid, under well-defined conditions and the burning persistence is measured after the flame is removed. The test described in section 3.2.2 of [11], "Determination of flame propagation in a fluid + coal dust mixture" was also used to estimate this risk. A volume of fluid is mixed with well-specified coal dust, the mixture is placed in a suitable container to form a long test piece, the mixture is lit and the propagation length is measured. The correlation between the test with the wick and the one with the coal dust is good, but the passage of one does not invariably indicate the passage of the other.

FM test with fluid-impregnated wick simulates and accident and can be briefly described as follows: information on self-extinguishing and propagating the flame, with a flame as ignition source, for a fluid soaked substrate.

Some FM tests involve soaking a substrate in fluid and applying a source of ignition. A general type is called the wick test, which is widely used in Europe as a test method in ISO 14935:1998 [33], adopted in the European Union and Romania in 2003. In this ISO test with immersed wick, a flame retardant ceramic tape is soaked in the test fluid. A pilot flame is then applied to the wick and then removed. Flame propagation along the wick and the time required for self-extinguishing are reported as test results. The ISO test with immersed wick is an important element of the test procedure given in [24].

3.4. Tests for determining the oxigen index

One method of interest was the evaluation of the hydraulic fluid fuel on the basis of the oxygen index, which has come into use in recent years when evaluating the combustible materials of polymers for different uses. This method consists in determining the minimum oxygen concentration that will maintain a stable combustion of the material. In Kruglov's work [41], the oxygen index was determined in an particular installation and the gas flow velocity in the working chamber was 3 cm/s.

The Oxygen index (OI) was defined as the minimum oxygen concentration (in %) that would ensure stable fluid burning and flame propagation along the string. Based on values obtained for the oxygen index, tested fluids can be divided into three groups: group I (OI=16.8…17.4) for fluids based on mineral and synthetic hydrocarbons and carboxylic acid esters, group II (OI=18.9...20) composed of polysiloxane-based fluids, group III (OI=23.2…26) is composed of phosphate-based fluids.

Because air at atmospheric pressure contains ~21% oxygen, fluids with OI = 21 will not maintain combustion under normal atmospheric conditions and will not propagate the flame when they are scattered and they are classified in group III.

3.5. Tests on ignition of flammable vapors (flash point)

The ease with which the vapors above a fluid can ignite is measured by the "flash point" (the lowest temperature at which by applying a test flame directed to a container containing the fluid, it causes the vapors to ignite above the fluid). Indirectly, it is a measure of both the volatility of the fluid and the flammability of the volatile substances contained in it. Several methods are used to determine the flash points of different fluids [42], including:

- the flash point - Test method IP 33 - IP 170 Abel automatic flash point tester,
- flash point with Setaflash closed tester - IP 303,
- the flesh point determined with the Pensky-Martens closed cup, ISO 2719:2002 [43] and IP 34 [83];
- flash point and fire point using the Cleveland open container: BS EN ISO 2592 [34], also recommended in HSE Approved specifications [11];
- the flash point (open cup) and the fire point with the Pensky - Martens, IP 35.

Care should be taken not to confuse the method used to determine the ignition point because different tests do not necessarily give the same results [24].

Typically, the flash point is measured using standardized test methods either in open or closed vessels [42]. Both open and closed vessel tests involve heating a sample in a small vessel at a set temperature. The pilot flame is inserted at the surface of the sample and it is observed whether or not the ignition occurs. During the test to determine the flash point in an open vessel, several volatile components of a multi-component mixture may be lost before the ignition source is applied. As a result, open vessel methods may overestimate the flash point of a sample containing several components. However, open-vessel tests can provide representative flash point data for open vessels and leaks. In contrast, closed-vessel testing techniques prevent the loss of volatile components by keeping the sample in closed form until the ignition source is introduced. The balance between liquid and vapor can be established in the test apparatus, ensuring that the temperature rise rate is low. Therefore, the data on the flash point determined in the closed vessel are more conservative than those obtained in the open vessel and generally more preferred.

There are several standard test methods in the closed vessel for measuring the flash point, which can be classified into non-equilibrium and equilibrium methods [44]. In non-equilibrium test methods, a closed test vessel is placed in an isothermal fluid bath or isothermal chamber. When selecting a fluid by its flash point, also the test method has to be the same.

ASTM E918-83 (2005) Standard Practice Method for Determining Flammability of Chemicals at Elevated Temperature and Pressure [45] and ASTM E1232-02 Standard Test Method for Temperature Limit of Flammability of Chemicals [46] define the lower flammability limit (LTL) as the lowest temperature, corrected to the pressure of an atmosphere, where the application of a source of ignition determines that a homogeneous mixture of oxidants in gaseous state and vapors in equilibrium with a liquid or solid will ignite and propagate a flame from the source of ignition under the specified conditions of test. Instead of a flame based on gaseous hydrocarbons, the ignition source is an electric arc or a loop of copper wires. Due to the fact that the ignition sources used in standard testers to determine the flash point in a closed vessel (gas flame), and that the electric arc and safety wire used in ASTM E1232 have sufficient energy. LTL of the sample measured using the ASTM method E1232 will be the same as the flash point measured using test methods for the flash point under equilibrium conditions.

When measuring the flash point of a fluid in an oxidizing gas or air [42], a common problem of standard test methods in a closed vessel is to establish and maintain the oxidizing gas or oxidizing gas mixture in the tester. There are some limitations in closed-vessel tests. Some closed vessels are not sufficiently tight. Therefore, the oxidizing atmosphere in the testers is difficult to maintain, which affects the accuracy. As soon as the pilot flame is inserted into the closed vessel, some portions of the flammable vapors are exposed to the surrounding air, affecting the measurement accuracy. When using standard sealed vessels, the oxidizing gas can escape forming an atmosphere rich in oxidants around the plant. This can lead to a more dangerous working environment in the laboratory, especially when toxic gas is involved.

3.6. FM Global test for evaluating the fire resistance of fluids

The CN 6930 standard [47] classifies the fire resistance of fluids by the value of the spray flammability parameter (SFP), a calculated value derived by evaluating the flammability characteristics of the fluid, from determinations of the rate of chemical heat.

The SFP test is based on the thermodynamic concept which shows that when a substance burns, it releases a certain amount of energy [1], [17] and a certain amount of energy is required to ignite a material. If the released energy is less than the energy required for ignition, then, by definition, the material cannot maintain a flame. SFP calculates a ratio of these two energies according to the equation:

$$\mathrm{SFP}_{(\mathrm{normalized})} = 11.02 \cdot 10^{6} \cdot \frac{Q_{ch}}{p_f \cdot q_{cr} \cdot m_f} \tag{1}$$

where Q_{ch} – the rate of release of the chemical heat, q_{cr} – the critical heat flux for ignition, p_f – fluid density; m_f – the mass flow rate of the fluid during the measurement of the release of the chemical heat. The last mass flow factor (m_f) was added to normalize the mass flow variation during the heat release test. This is why the result is given asAcesta este motivul pentru care $\mathrm{SFP}_{(\mathrm{normalized})}$, with measure unit as s/g.

The critical heat flux can be estimated by measuring the fire point of the fluid. This is important because the fire point is a fast and well-known test, while direct measurement of critical heat flux is time-consuming and test equipment is not readily available.

The rate of release of chemical heat is calculated by measuring the carbon monoxide and carbon dioxide generated. At a minimum, the first and last 30 seconds of each test are excluded from the measurements used in the calculations. The FM standard [49] has an approximation of the rate of release of chemical heat, which can be obtained using an oxygen pump calorimeter to determine the net heat of the complete combustion, which can be used as a value "close" to that of the chemical heat [36].

The critical heat flux for ignition (q_{cr}) of the tested fluid is determined by exposing the tested fluid to radiant heat during the ignition test. A 100 ml sample of the fluid is placed in a cylindrical aluminum bowl, placed on a platform surrounded by radiant electric heaters. Radiant heaters are capable of providing radiant heat flow to the fluid surface of 0...60 kW/m^2. The fluid is subjected to four or more different values of the radiant heat flux and the different exposure times required for sustaining ignition of the vapors are recorded. Increasingly lower values are used for radiant heat until the ignition time is greater than 15 minutes of exposure. A graph of the times required for ignition as a function of the radiant heat flux is done and the line or curve best suited through the points obtained is called the critical heat flux for ignition of the fluid.

3.7. Tests of Flammability on hot surface

CETOP RP65H "Manifold Ignition test for Fire-resistant Fluids" [49] was considered appropriate to estimate this hazard in [11]. In this test, the fluid is dripped onto a tube heated to 704 °C and the observations refer similarly as ISO 20823 [39]. All technical recommendations CETOP are no longer valid since 21.06.2002 and are officially withdrawn.

Studies on ignition on hot surfaces were performed without being standard, by Khan et al. [50], [51], Toy et al. [52], Hamins, Borthwick and Preser [53], Deleanu [54], Yuan [55], the last one determining the minimum oil temperature and the minimum spray jet pressure for which the ignition is obtained. Wright, Mowery and LePera [56] present an approach to the problem of hydraulic fluids in critical situations where survival depends on the fire resistance properties of these fluids, especially related to military equipment. in addition to spray ignition tests, the hot surface ignition test is also presented. Federal Test method 791, method 6053.1 [57] determines the flammability of a fluid in contact with a hot surface. From the specialized literature, this is the closest procedure in terms of method and quantification of the results with ISO 20823:2003.

Standard ISO 20823 specifies a test method to determine the flammability of fluids when they come into contact with a hot metal surface, at a certain temperature, but it is also possible to determine the ignition temperatures of the fluid by adjusting the temperature manifold. The principle of the test method implies a fluid sample of 10 ml dripping from a predetermined height, for 50s ± 10s, at a controlled drip rate, on a tube heated to 700 °C ±5 °C or at another temperature. The result is examined from the point of view of ignition or combustion, both on the tube and after leaking from it. The results should be included in one of these categories: "I (T)" when the fluid ignites or burns on the tube, but does not continue to burn when collected in the tray below, "I (D)" when the fluid ignites and burns on the tube, and continues to burn when collected in the tray below or "N" when the fluid does not ignite or burn at any time.

4. THE 7TH LUXEMBOURG REPORT FOR EVALUATING THE FIRE RESISTANCE OF FLUIDS

The requirements of the test method for the fire resistance of the hydraulic fluid in accordance with the 7th Luxembourg Report are [24]:

- a pressure spray test in accordance with the 7th Luxembourg Report (3.1.1) or with the United Kingdom (ISO 15029-1, 7th Luxembourg Report 3.1.2);
- spray tests in accordance with "stabilized flame heat release" (7th Luxembourg Report 3.2.2);
- the persistence tested of the flame on a wick (7th Luxembourg Report 3.2.1) or the determination of the flame spread of a sprayed mixture (7th Luxembourg Report 3.2.2).

In a combustion chamber with air circulation, a spray jet of test fluid and pressurized air is exposed to a well-defined flame of propane burner. The temperatures of the fresh air and the flue gases are measured while the burner is lit, both with and without fluid coming out through the nozzle.

The relative fire resistance in terms of an ignition factor (RI) is given by measuring these outlet temperatures during the combustion of the tested fluid. Two propane flows are used to differentiate between fluids. The ignitability factor without correction (R_{IW}) is determined on the hydraulic fluid tested with a propane flow rate of 0.13 Nm^3/h, using equation (2).

If an ignitability index $RI_W < 50$, then the burner flame is generated by a propane flow rate of 0.13 Nm3/h and the calculation is done as:

$$RI_W = 500 \cdot \left(T_p - T_{a1}\right) / 7 \cdot \left(T_{ex} - T_{a2}\right) \qquad (2)$$

where T_p - exhaust temperature of the propane burner without spray; T_{a1} - air inlet temperature at the combustion chamber without spray; T_{ex} - temperature of burning gas jet; T_{a2} - air temperature at the combustion chamber entry with spray (all temperatures in C).

Table 1. Degrees of fluids [24]

D RI	Range for RI
A	>100
B	100 – 80
C	79 – 65
D	64 – 50
E	49 – 36
F	35 – 25
G	24 – 14
H	<14

If an ignitability index has a value $RI_W > 50$ as calculated with relation (2.5), the result is not included and a new test is done with a flame generated by a propane flux of 0.4 Nm^3/h. The RI becomes:

$$RI_W = \left[100 \cdot \left(T_p - T_{a1}\right) / \left(T_{ex} - T_{a2}\right)\right] + 30 \qquad (3)$$

Minimum eight measurements of RI have to be done for fluid for getting the accuracy required by the7-lea Report Luxemburg. The ignition factor RI is graded at intervals, with the least flammable fluids with a symbol A and even the most flammable with the symbol H (Table 1) [78].

Today, there are only a few tested fluids that have been evaluated according to the standards described in both the 7th Luxembourg Report and the FM Approvals 6930 standard. The available results generally indicate a correlation (Table 2) [12, 13, 24, 47].

Table 2. Fluid classification [12], [13], [24], [47].

Tipul de fluid hidraulic rezistent la foc	Clasificarea FGM pe bază CN 6930 (ianuarie 2002)	RI degree as in the 7th Luxemburg Report 3.1.3.6
HFA	Grupa 0	A
HFB	Grupa 1	D – E
HFC	Grupa 1	B – C
HFDR	Grupa 1	D – E
HFDU	Grupa 2	G – H

Sherman [30] agrees that two of the world's most recognized standards for the certification of fire-resistant hydraulic fluids for general industrial applications are and will be: Luxembourg Report [24] and FM Approvals 6930 [47]. The two methods differ significantly in the conceptual approach in differentiating fire resistant hydraulic fluids. The FM Approvals 6930 standard has only two classifications for fire resistance and has two very different methodologies, one for water-containing fluids and the other for anhydrous fluids. The 7th Luxembourg Report and the corresponding ISO standards have eight ratings for fire resistance, using the spray heat release test. The test method is used for both water-containing and anhydrous hydraulic fluids. Initial data on the reproducibility and repeatability of the test method are positive. These differences and the lack of available data on specific batches of hydraulic fluids evaluated with both standards do not allow a true comparison at this time.

5. RISK ASSESSMENT AND ADVISABILITY OF FLAMMABILITY TESTS

For establishing safety regulations worldwide, a new approach is required in which the choice of a fluid is made through a risk-based approach [31]. It can include information from a range of tests and allows the inclusion of other methods of applying appropriate fire safety standards, such as fire protection or automatic fire extinguishing systems. Thus, new fire test requirements are required to provide the necessary data for risk assessment as well as a new fluid selection approach.

The range of fluids selected for the risk assessment program in [31] was representative for generic types in the UK: a mineral oil, diluted ethylene glycol, oil-water emulsion, polyphosphate ester, polyglycol ether, polyolester and rapeseed oil derivatives. A test program was assembled with the ignition tests in Table 3.

Table 3. Test program for evaluating the flammability characteristics (ignition) [31]

Testul	Sursa de fluid/aprindere	Măsurători
Ignition of a spray jet towards an open flame (ISO 15029-1).	Spray at 1000 psi pressure through a nozzle, with open flames that range from the equivalent of a match stick to a soldering lamp.	Size and speed of heat release, ignition source, occurrence and position of any ignition
Ignition of a spray jet from a spark	Spray as above. Sparks in the range 2 mJ – 2 J	Occurrence, energy and position of any ignition in spray
Ignition of a spray jet on a hot surface	A variety of sprays, including one from ISO 15029-2 on flat hot plates, with temperatures up to ~600 °C, monitored with infrared equipment.	The hot surface is sprayed, varying the inclination and surface temperature up to ~ 600 °C. Any ignition will be noted.
Ignition of the fluid with open flame	A stream of fluid spilled from a vessel on a sloping plate, with an open flame.	Observation of any ignition, time to ignition and position of each ignition
Ignition of the fluid on hot surface ISO 20823:2003	A stream of fluid spilled over an inclined tube. The tube is heated to temperatures up to 700 °C	Tube temperature at which ignition occurs, the persistence of flame on tube or/and in the tray.
AIT (fluid self-ignition temperature) DIN 51 794	dropping fluid	self-ignition temperature
Ignition of a fluid soaked in a textile waste. UN Test 4	Fluid soaked in mineral wool and heated in an oven for a period of time, at a rising temperature	The temperature, the exposure time and the occurrence of any heat release
Fluid ignition on absorbent medium (ISO 14935)	Fluid-soaked wires. Various ignition sources (open flame).	ignition characterization of wires

The test program was selected using a number of criteria. An attempt was done to reflect the conditions of use by particularizing types of leaks, including sprays at high pressures, fluid soaked in absorbent material and static accumulations, using ignition sources of representative sizes and energies, including open flame, hot surfaces and electrical spark. Tests were required to provide a range of measured data on ease of ignition and major fire hazards: rate of fire increase, rate of heat release and rates of smoke and toxic substances generation. By following such a program, tests can be critically reviewed on their scientific basis and the usefulness of the data for their use in risk assessment. [58], [59], [60].

The determination of what means "less dangerous" or "less risky" is done by subjecting the fluids to accepted tests, the results giving a certain quantitative measure of their fire resistance. The term "fire resistant" must be supported by test methods that are relevant to the application in which the fluid is used and should not be taken solely as a nominal value. Users should select fluids based on tests, their own assessment and experience, available data.

Taking into account the consulted literature and standards, it can be stated that no test can provide a complete characterization of fire resistance of a fluid. The designer and the responsible with work security has to promote a set of appropriate tests for avoiding ascertainable hazards for a particular application.

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