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Autor: Breugel, Klaas van

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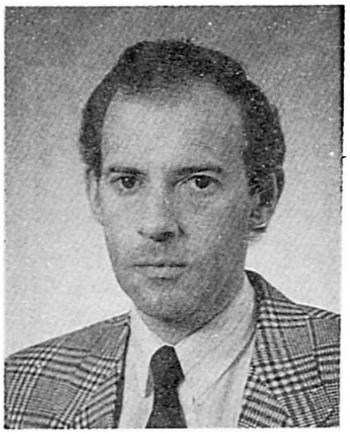
Concrete Structures for Risk Reduction on Industrial Plants

Ouvrages en béton pour réduction du risque des complexes industriels

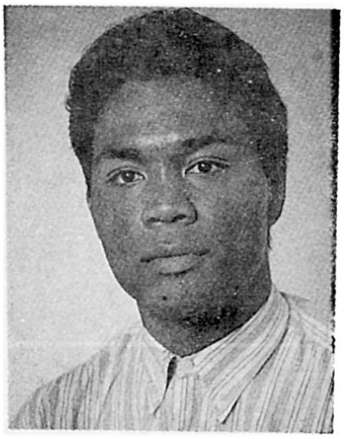
Betonbauten zur Risikominderung in industriellen Anlagen

Klaas VAN BREUGEL
Civil Engineer
Techn. Univ. Delft
Delft, the Netherlands



Klaas van Breugel, born 1952, received his Engineering degree at the Delft University of Technology in 1979. Since then lecturer and researcher involved in problems of early-age concrete (PhD, 1991) temperature effects and concrete structures for environmental protection.

Melvin ASIN
Civil Engineer
Techn. Univ. Delft
Delft, the Netherlands



Melvin Asin, born 1966 received his masters degree at the Delft University of Technology in 1990. For one year involved in structural analysis of spherical structures under fire loading. At present employed at the university of Delft as researcher.

SUMMARY
Increasing number, scale and complexity of industrial facilities and the associated high risk potentials compel us to reconsider current safety concepts. A major point in this respect refers to the recognition that in case of Low Probability/High Consequence Risks risk reduction should be achieved primarily, may be exclusively, by reduction of the consequences. For reliable consequence reduction concrete protective structures with high built-in passive safety potentials offer most challenging prospects. The safety potentials of prestressed concrete pressure vessels for industrial use will be highlighted.

RÉSUMÉ
L'augmentation continue du nombre, de l'importance et de la complexité des installations industrielles et des risques potentiels en résultant, oblige à réviser les conceptions de sécurité actuelles. Il semble logique de penser que la maîtrise des conséquences doive entraîner en principe, voire à coup sûr, la réduction des risques dans le cas d'un rapport de faible probabilité à haut potentiel de risques. Par suite de leur sécurité passive inhérente, les constructions en béton précontraint sont fort bien appropriées pour réduire avec efficacité les dommages consécutifs. Ceci est illustré par un exemple de réservoirs sous pression réalisés en béton précontraint.

ZUSAMMENFASSUNG
Die immer grösser werdende Anzahl und Komplexität von industriellen Anlagen und die damit verknüpften Risiken zwingen zum Überdenken heutiger Sicherheitskonzepte. Gefährdungen geringer Eintretenswahrscheinlichkeit aber grossen Schadenpotentials sollten vornehmlich — wenn nicht ausschliesslich — durch die Beherrschung der Auswirkungen vermindert werden. Für Schadenbegrenzung sind Bauten aus vorgespanntem Beton, infolge ihrer vorragender passiven Sicherheit, sehr geeignet. Dies wird illustriert an Druckbehältern aus vorgespanntem Beton.

1. RISK CRITERIA AND RISK REDUCTION: SOME INTRODUCTORY REMARKS

For the evaluation of risk potentials in modern industrial facilities Quantitative Risk Analysis (QRA) has become increasingly popular. The QRA has turned out to be a most valuable tool for comparison of safety levels and for tracing the weak points in industrial processes and structures. Less emphasized, but of great importance in view of present and future safety considerations, is that QRA has taught us that past striking accidents must, in essence, be considered merely as precursor events and that more, and even more severe, accidents are bound to happen [1,2]. These penetrating lessons compel to reconsider current safety strategies and the role of QRA in them.
A major point of concern in this process of reconsideration refers to the eloquence of often adopted single-valued risk criteria. Among them the *fatality rate*, being the number of fatalities per accident multiplied by the event probability, is probably the one most frequently used. The charm of a single-valued acceptance criterion is certainly its relative simplicity. Simplicity, however, is not necessarily the hall-mark of truth. Recent industrial catastrophes have demonstrated convincingly that consequences *cannot* merely be expressed in terms of fatality numbers and that, consequently, a risk criterion *shall* not be expressed merely in terms of fatality rates. Also other consequence aspects, like *social*, *environmental*, *economical*, *political* and *cultural* aspects, to mention only a few, should be considered in the evaluation of risk bearing activities [4]. Moreover - and this is considered to be a major point of concern - a single-valued risk criterion offers the possibility to meet this criterion by reducing the *event probability*, leaving the "multi-aspect character" of the consequences unconsidered.

> *QRA, if used to as an tool to prove that a single-valued risk criterion can be met, must be considered as a vehicle for acceptance or introduction of all kinds of risk bearing activities which might be or should have been judged unacceptable for may be a number of other relevant reasons.*

It is particularly in case of Low Probability/High Consequence Risks that a single-valued risk criterion must be considered as inadequate. In those cases *risk reduction* should not be achieved by reduction of the *event probability*, but primarily by reduction of the *consequences* [5]. It is particularly in view of control and reduction of consequences that the potentialities of concrete structures will be discussed in this paper. This discussion is focussed on the potentialities of Prestressed Concrete Pressure Vessels (PCPVs) for storage of hazardous products to resist extreme thermal loads.

2. WHY PRESTRESSED CONCRETE PRESSURE VESSELS FOR STORAGE OF HAZARDOUS PRODUCTS

Accident statistics show an increase of the number of large-scale industrial accidents [4]. An evaluation of these accidents reveals, firstly, that in many cases storage vessels were involved and that, secondly, the failure of pressure vessels has often contributed significantly to the escalation of accidents into major catastrophes. The relatively low impact and fire resistance of traditionally built steel pressure vessels appears to be the main cause of these vessel failures [9]. Increasing the impact and fire resistance of pressure vessels would undeniably result in a reduction of the vulnerability of industrial facilities and hence in a reduction of the consequences and risks of large accidents. The high built-in impact resistance and insulating capacity of PCPVs would offer good prospects in view of enhancement of safety.
An example of a PCPV is shown in Fig. 1. The vessel is built of eight prefabricated segments. After these elements are brought in position prestressing tendons are installed in a stress-free state. The tendons are coupled at the "expansion" joints between the segments. At the inside of the vessel a tight liner is installed allowing substantial movements at the expansion joints. After installation of the liner the vessel is blown up until the strains ex-

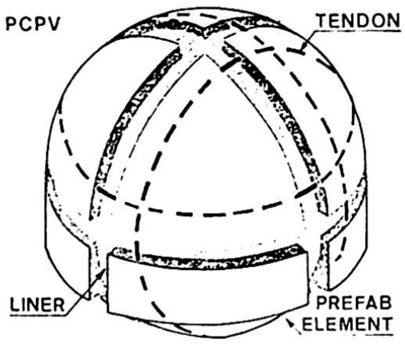


Fig. 1 Prestressed Concrete Pressure Vessel. Original concept after [3].

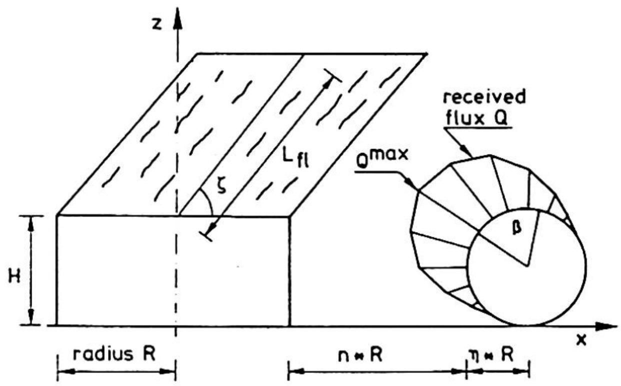


Fig. 2 Scenario of large-scale tank fire as considered by BOLCRYO [6].

erted in the prestressing tendons have reached the required design value. The expansion joints are then filled with concrete. After hardening of the concrete the pressure is relieved and the concrete is put in a stressed state. For a PCPV built according to just outlined procedure and which meets the test requirements for steel pressure vessels imposed by the Dutch Boiler Inspectorate the safety factor in the operational stage has been calculated at γ=2.8.

3. PCPVs UNDER FIRE LOADING AND ASPECTS OF THERMAL DESIGN

3.1 Fire scenario, heat flux and temperatures

For the determination of the temperature distribution in a spherical vessel a computer code called BOLCRYO has been used. In this code the influence of the emissive power at the flame surface, the relative humidity of the air, the wind velocity (flame inclination) and the surface characteristics of the target are accounted for. For the fire scenario sketched in Fig. 2 the radiation intensity Q^{max} received by a vessel and the associated temperatures in the concrete shell are shown in the figures 3 and 4. Wind velocity and tank distance are inserted as parameters. The tank distance is indicated by the tank distance factor n, being the distance between the sphere and burning (cylindrical) vessel divided by the radius of the burning tank. From Fig. 4 it can be seen that due to the cooling effect of the wind the maximum temperature does not necessarily coincide with the maximum flux. Temperature distribution over the thickness of the shell after 10 hrs is shown in Fig. 5.

3.2 Safety considerations

In case of *mechanical loads* (dead weight, live loads, etc.) structural safety

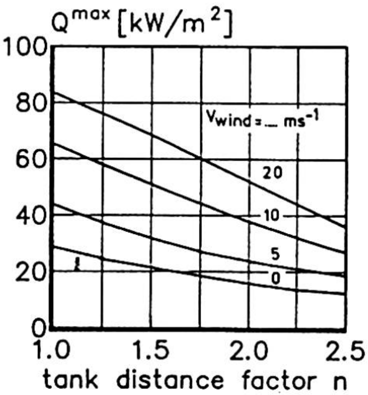


Fig. 3 Maximum heat flux Q^{max} received by a spherical vessel [6].

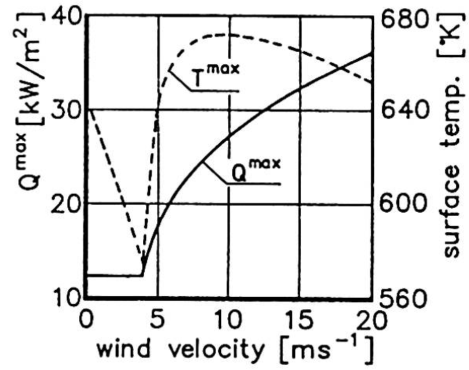


Fig. 4 Max. heat flux and surface temperature. Wind velocity as parameter.

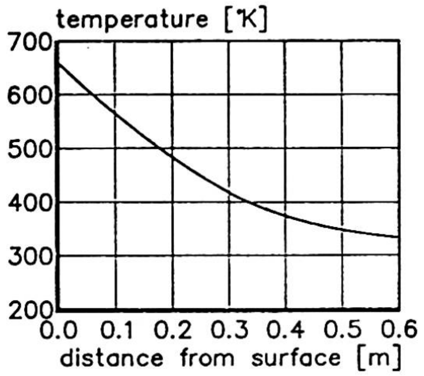


Fig. 5 Temperature distribution over the shell thickness after 10 hrs [6].

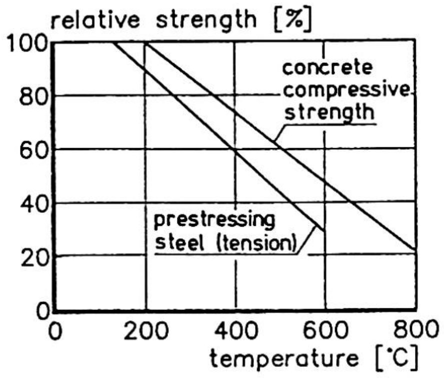


Fig. 6 Temperature dependency of concrete and steel strength (after [8].

is defined as the quotient of strength and load-induced forces, c.q. stresses. It is well known that in case of non-linear systems safety considerations shall take into account that local plastic deformations are acceptable as long as stability is guaranteed. This holds primarily for statically indeterminated structures but also, on cross-sectional level, for statically determinated systems. In sections where excursions in the plastic zone occur, the value of the *local* cross-sectional safety factor is $\gamma=1$!

When dealing with *imposed deformations* the failure criterion shall, in essence, be defined in terms of strains. In case of a combination of mechanical loads and imposed deformations both the strength and the strain criterion shall be checked. For *linear* and *brittle* systems (no yielding branch) the effects exerted by mechanical loads and imposed deformations can be added and compared with either the ultimate strength or the ultimate strain. Because of the linear character of the system both comparisons will yield the same safety factor. In case of *non-linear* systems, with either a plastic, a softening or a hardening branch, a comparison of the added effects of both types of actions with either the ultimate strength or ultimate strain does *not* give us reliable information about the actual safety. Adding, for example, the cross sectional forces caused by a mechanical loading and an imposed thermal deformation and comparing the summarized forces with the strength capacity will, in case of ductile systems, result in an *underestimation* of the actual safety, i.e. in a *conservative design* in so far as safety is concerned. This conservative approach is still proposed in the new EUROCODE 2. Bearing in mind its just elucidated shortcomings, the conservative approach will be applied now for judging, conservatively, the safety of PCPVs.under extreme fire loads.

In addition to foregoing considerations an evaluation of safety under thermal loads should take into account the *temperature dependency* of the material properties. The strength-temperature relationships of concrete and prestressing steel adopted in the present analysis are shown in Fig. 6 [8].

4. STRUCTURAL RESPONSE AND SAFETY OF A PCPV UNDER FIRE LOADING

For preliminary investigations of temperature-induced forces in a spherical vessel (3,000 m^3) a simple model was used as shown in Fig. 7. Two perpendicular rings of the sphere are considered, loaded by the internal overpressure caused by stored product (LPG: operating pressure ≈ 14 bar), and the external fire load. Because of the non-symmetrical character of the fire load the temperature induced deformations of individually expanding rings are not identical. To establish compatibility of deformations and equilibrium of forces two different concepts have been adopted [6]. In the first concept (I) compatibility and equilibrium are established by application of cross-sectional forces,

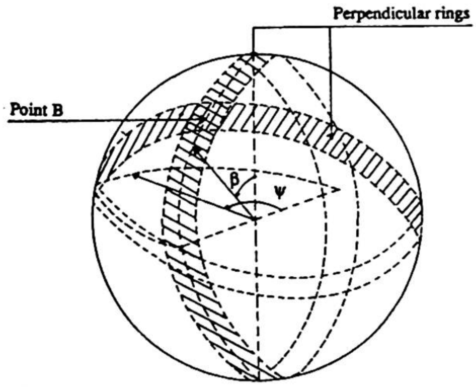


Fig. 7 Model used for preliminary investigations of the fire-caused forces [6].

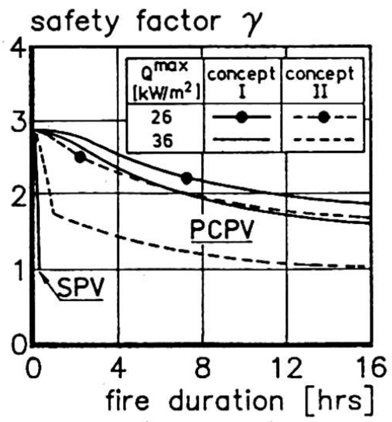


Fig. 8 Decrease of safety factor γ with fire duration. a) Steel vessel; b) Prestressed concrete vessel. (n = 2).

i.e. flexural moments, shear forces and normal forces at the point of symmetry, i.e. point B, of the rings. In the second concept (II) compatibility and equilibrium are achieved by application of fictitious, radially oriented distributed loads. In this concept high ring forces are exerted, viz. compression in the large ring and tension in the smaller one. In this way the occurrence of membrane forces in a non-symmetrically loaded sphere is simulated, albeit in a conservative way. The thus determined forces are added to the forces exerted by the stored product.

Of major interest in view of safety are the membrane forces. The calculated membrane forces divided by the temperature-dependent membrane strength of the rings yields the safety factor γ. The development of this safety factor with the duration of the fire is shown in Fig. 8. Two values of the maximum heat flux Q^{max} were considered, viz. 26 and 36 kW/m², the latter value simulating a very severe thermal loading. In Fig. 8 a comparison is made between the calculated safety factor of a steel pressure vessel (SPV) and a PCPV. A SPV would fail after about 10 minutes. This is in good agreement with experimental work of Droste and Schoen [7] and with what has been observed in a large number of industrial accidents. For a PCPV, submitted to the same fire loadings, the initial safety factor γ = 2.8 dropped to about 1.6 after 16 hrs, the safety factor being defined according to concept I. For the most conservative concept II a substantial increase in safety as compared to the steel pressure vessel was still found, even in case of the most severe thermal loading.

A more detailed analysis of the behaviour of the vessel under fire load reveals that the temperature induced forces hardly affect the actual safety of the vessel. The major reason for vessel failure is the temperature induced *decrease* of the strength of the load bearing prestressing cables.

5. PROBABILISTIC ANALYSIS OF DOMINO EFFECT IN A FICTITIOUS TANK FARM

The favourable structural behaviour of PCPVs under fire loads has been inserted in a probabilistic analysis of the probability of a catastrophic domino effect in a fictitious tank farm. The tank farm consists of twelve 3,000 m³ LPG pressure vessels and one 36,000 m³ double walled (steel/concrete) cryogenic tank. The spheres were considered to be built as either SPVs (wall thickness 37 mm) or PCPVs (wall thickness >600 mm). In total 24 initiating events and associated accident scenarios were considered, including rupture of piping, several BLEVEs (Boiling Liquid Expanding Vapour Cloud Explosions) and aircraft impact (Phantom II). The event probabilities were taken from open literature [9]. The results of the probabilistic analysis were compared with the results of a more phenomenological approach based on accident statistics [4,9].

The results of both the probabilistic and the phenomenological approach are summarized in Table 1. The probability of failure of one single SPV was calculated at 2.9 10^{-5}/yr and of a PCPV at 4.0 10^{-7}/yr. It is remarked that the probability of failure of one single PCPV is largely determined by the aircraft impact. The probability of a major domino effect involving all SPVs was calculated at 3.5 10^{-4}/yr. This figure was found to be in relative good agreement with the value obtained from the phenomenological approach, viz. 4.1 10^{-6}/yr. *No* realistic scenario could be compiled in which all PCPVs would fail catastrophically in one single accident!

Table 1 Probability of catastrophic domino effect in fictitious tank farm

Number of vessels n	probability of failure		
	traditionally built steel pressure vessels		prestressed concrete pressure vessels
	phenomenological	probabilistic	probabilistic
1	3.6 10^{-5}/yr	2.9 10^{-5}/yr	4.0 10^{-7}/yr
12 (domino)	4.1 10^{-6}/yr	3.5 10^{-4}/yr	*incredible*

6. CONCLUDING REMARKS

One of the corner stones of risk reduction is consistent scenario thinking. Consistent and comprehensive scenario thinking teaches us that in case of Low Probability/High Consequence Risk the consequences of an accident might exceed acceptable limits. This makes that risk reduction should be achieved preferably, in some case *exclusively*, by reduction of the consequences *irrespective* of the event probability. Concrete protective structures, due to their built-in *passive safety potentials*, are most adequate for an almost deterministic control of consequences and, implicitly, for reduction of risks. As indicated in this paper PCPVs, because of their high built-in insulating capacity, substantially contribute to the reduction of the consequences and risks in large-scale industrial accidents. And this, as several independent studies have revealed, without an increase of the building costs [3,9].

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