CONCRETE STORAGE

VESSELS

State of the art report

Prof. dr. ir. A.S.G. Bruggeling

Technische Universiteit Delft
Faculteit CiTG
Bibliotheek Civiele Techniek
Stevinweg 1
2628 CN Delft

Technische Hogeschool Delft
Afdeling der Civiele Techniek

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<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>PREFACE</td>
<td>9</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>11</td>
</tr>
<tr>
<td>SAMENVATTING</td>
<td>13</td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>15</td>
</tr>
<tr>
<td>1.1 Objective of this report</td>
<td>15</td>
</tr>
<tr>
<td>1.2 Gases and liquids with which this report is concerned</td>
<td>15</td>
</tr>
<tr>
<td>1.3 Subdivision of this report</td>
<td>20</td>
</tr>
<tr>
<td>1.4 Limitations of this report</td>
<td>22</td>
</tr>
<tr>
<td>2 ASPECTS OF &quot;UNPRESSURIZED COOLED STORAGE&quot;</td>
<td>25</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>25</td>
</tr>
<tr>
<td>2.2 Storage systems</td>
<td>26</td>
</tr>
<tr>
<td>2.2.1 Single-walled tank</td>
<td>26</td>
</tr>
<tr>
<td>2.2.2 Double-walled tank</td>
<td>28</td>
</tr>
<tr>
<td>2.2.3 Safety wall</td>
<td>29</td>
</tr>
<tr>
<td>2.2.4 Integrated tank</td>
<td>30</td>
</tr>
<tr>
<td>2.2.5 Underground and/or earth-protected tanks</td>
<td>31</td>
</tr>
<tr>
<td>2.3 Possible problems</td>
<td>32</td>
</tr>
<tr>
<td>2.3.1 Internal causes</td>
<td>33</td>
</tr>
<tr>
<td>2.3.1.1 Gas overpressure</td>
<td>33</td>
</tr>
<tr>
<td>2.3.1.2 Gas underpressure</td>
<td>34</td>
</tr>
<tr>
<td>2.3.1.3 Overfilling</td>
<td>35</td>
</tr>
<tr>
<td>2.3.1.4 Errors in design, construction and materials</td>
<td>35</td>
</tr>
<tr>
<td>2.3.2 External causes</td>
<td>36</td>
</tr>
<tr>
<td>2.3.2.1 Fire in the vicinity</td>
<td>36</td>
</tr>
<tr>
<td>2.3.2.2 Explosion in the vicinity</td>
<td>37</td>
</tr>
<tr>
<td>2.3.2.3 Fragments hurled away</td>
<td>37</td>
</tr>
<tr>
<td>2.3.2.4 Sabotage</td>
<td>38</td>
</tr>
<tr>
<td>2.3.2.5 Aircraft, etc.</td>
<td>38</td>
</tr>
<tr>
<td>2.3.2.6 Natural phenomena</td>
<td>38</td>
</tr>
</tbody>
</table>
2.4 Undesirable consequences
  2.4.1 Burning contents of tank
  2.4.2 Escape of gas
  2.4.3 Outflow of liquid
  2.5 Review of possible problems

3 PROPERTIES OF CONCRETE AND CONCRETE STRUCTURES
  3.1 Concrete
    3.1.1 General
    3.1.2 Properties
      3.1.2.1 Low temperatures
      3.1.2.2 Liquid-tightness
      3.1.2.3 Vapour-tightness
      3.1.2.4 High temperatures
      3.1.2.5 Temperature changes
  3.2 Reinforcing steel, prestressing steel, anchorages
    3.2.1 General
    3.2.2 Reinforcing steel
    3.2.3 Prestressing steel
    3.2.4 Anchorages
  3.3 Reinforced concrete
  3.4 Prestressed concrete
  3.5 Fibre-reinforced concrete
  3.6 Impact loads, hits, etc.
  3.7 Axial compressive and tensile impact loads
  3.8 Temperature variations
    3.8.1 Thermal behaviour of concrete
    3.8.2 One-sided heating by radiant heat
    3.8.3 One-sided cooling by cold liquid
  3.9 Choice between reinforced concrete and prestressed concrete
    3.9.1 Ordinary conditions during use
    3.9.2 Special conditions during use
    3.9.3 Possibility of sudden failure of a concrete tank
3.9.3.1 Reinforced concrete wall 94
3.9.3.2 Prestressed concrete wall 95
3.10 Insulating materials 97
3.10.1 Insulating materials in granular form \( I_p \) 97
3.10.2 Coherent insulating materials (loadbearing insulation) 97
3.10.3 Review of available insulating materials 98

4 STORAGE SYSTEMS AND FORMS-OF CONSTRUCTION IN CONCRETE 101
4.1 General 101
4.2 Double-walled steel tank, with insulation between inner and outer tank (SIS) and single-walled steel tank, with insulation on the outside (IS) 103
4.3 Double-walled steel tank, with insulation between inner and outer tank, and surrounded by a concrete safety wall (C--SIS) "Gap problems" 107
4.4 Single-walled steel tank, insulated on the outside and surrounded by a concrete safety wall (C--IS) 115
4.5 Single-walled steel tank, surrounded by a concrete safety wall which is insulated on the outside (CI--S) 119
4.6 Double-walled tank, with steel inner tank and concrete outer tank, and insulation between them (CIS) 123
4.7 Double-walled concrete tank, with insulation between inner and outer tank \( C_{\text{LICL}} \) 127
4.8 Single-walled concrete tank, insulated on the outside \( SIC_L \) 131
4.9 Single-walled concrete tank, insulated on the inside (CIL) 135
4.10 Single-walled concrete tank, insulated on the inside, and surrounded by a concrete safety wall \( C--CIL \) 141
4.11 Underground and/or earth-banked storage tanks 143
4.12 Tank standing free in a separate pit 149
4.13 Concrete roof structure 151
4.14 The optimum design 152
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>LOADS TO BE ADOPTED IN THE DESIGN CALCULATIONS</td>
<td>155</td>
</tr>
<tr>
<td>5.1</td>
<td>Design criteria</td>
<td>155</td>
</tr>
<tr>
<td>5.2</td>
<td>Ordinary loads (in normal use)</td>
<td>156</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Roof structure</td>
<td>157</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Wall structure</td>
<td>157</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Base structure</td>
<td>158</td>
</tr>
<tr>
<td>5.3</td>
<td>Special loads due to &quot;events of internal origin&quot;</td>
<td>158</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Overfilling</td>
<td>158</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Gas overpressure and underpressure</td>
<td>159</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Temperature shock or &quot;cold spot&quot;</td>
<td>159</td>
</tr>
<tr>
<td>5.3.4</td>
<td>Liquid impulse</td>
<td>159</td>
</tr>
<tr>
<td>5.3.5</td>
<td>Explosion in a gap (between tank and safety wall)</td>
<td>160</td>
</tr>
<tr>
<td>5.3.6</td>
<td>Tank contents on fire</td>
<td>160</td>
</tr>
<tr>
<td>5.4</td>
<td>Special loads due to &quot;events of external origin&quot;</td>
<td>161</td>
</tr>
<tr>
<td>5.4.1</td>
<td>Nearby fire</td>
<td>161</td>
</tr>
<tr>
<td>5.4.2</td>
<td>Nearby explosion</td>
<td>161</td>
</tr>
<tr>
<td>5.4.3</td>
<td>&quot;Impacts&quot;, &quot;hits&quot;, etc.</td>
<td>163</td>
</tr>
<tr>
<td>5.4.4</td>
<td>Natural phenomena and disasters</td>
<td>163</td>
</tr>
<tr>
<td>5.5</td>
<td>Load combinations and load factors</td>
<td>164</td>
</tr>
<tr>
<td>5.6</td>
<td>Requirements applicable to concrete storage tanks</td>
<td>166</td>
</tr>
<tr>
<td>5.6.1</td>
<td>Tank walls</td>
<td>166</td>
</tr>
<tr>
<td>5.6.2</td>
<td>Tank bases</td>
<td>167</td>
</tr>
<tr>
<td>5.6.3</td>
<td>Wall-to-base connection</td>
<td>167</td>
</tr>
<tr>
<td>5.7</td>
<td>Requirements applicable to concrete safety walls</td>
<td>167</td>
</tr>
<tr>
<td>5.7.1</td>
<td>Dimensions</td>
<td>167</td>
</tr>
<tr>
<td>5.7.2</td>
<td>Supplementary requirements</td>
<td>168</td>
</tr>
<tr>
<td>5.8</td>
<td>Test loads</td>
<td>169</td>
</tr>
<tr>
<td>5.8.1</td>
<td>&quot;Water test&quot;</td>
<td>170</td>
</tr>
<tr>
<td>5.8.2</td>
<td>&quot;Gas test&quot;</td>
<td>170</td>
</tr>
<tr>
<td>5.8.3</td>
<td>&quot;Cooling test&quot;</td>
<td>170</td>
</tr>
<tr>
<td>5.9</td>
<td>Summary</td>
<td>172</td>
</tr>
<tr>
<td>6</td>
<td>STRUCTURAL ARRANGEMENTS AND DETAILS</td>
<td>175</td>
</tr>
<tr>
<td>6.1</td>
<td>Foundation structures for concrete tanks</td>
<td>175</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>6.1.1</td>
<td>General</td>
<td>175</td>
</tr>
<tr>
<td>6.1.2</td>
<td>Raft foundation</td>
<td>176</td>
</tr>
<tr>
<td>6.1.3</td>
<td>Pile foundation</td>
<td>178</td>
</tr>
<tr>
<td>6.2</td>
<td>Wall-to-base connection</td>
<td>180</td>
</tr>
<tr>
<td>6.2.1</td>
<td>Deformations of the tank wall of prestressed concrete</td>
<td>180</td>
</tr>
<tr>
<td>6.2.2</td>
<td>Wall standing on base slab</td>
<td>181</td>
</tr>
<tr>
<td>6.2.3</td>
<td>Wall extending past base slab</td>
<td>184</td>
</tr>
<tr>
<td>6.2.4</td>
<td>Sliding wall-to-base connection (design criteria)</td>
<td>185</td>
</tr>
<tr>
<td>6.2.5</td>
<td>Liquid-tightness and vapour-tightness (sliding connections)</td>
<td>186</td>
</tr>
<tr>
<td>6.2.6</td>
<td>Transmission of vertical loads (sliding connections)</td>
<td>189</td>
</tr>
<tr>
<td>6.2.7</td>
<td>Transmission of horizontal forces (sliding connections)</td>
<td>190</td>
</tr>
<tr>
<td>6.3</td>
<td>Wall structures</td>
<td>192</td>
</tr>
<tr>
<td>6.3.1</td>
<td>Prestressing and reinforcing</td>
<td>192</td>
</tr>
<tr>
<td>6.3.2</td>
<td>Location and nature of the prestress</td>
<td>192</td>
</tr>
<tr>
<td>6.3.3</td>
<td>Steel liner</td>
<td>195</td>
</tr>
<tr>
<td>6.3.4</td>
<td>Pipes</td>
<td>196</td>
</tr>
<tr>
<td>6.4</td>
<td>Roof structures and wall-to-roof connections</td>
<td>197</td>
</tr>
<tr>
<td>6.4.1</td>
<td>Roof structures</td>
<td>197</td>
</tr>
<tr>
<td>6.4.2</td>
<td>Connection of concrete wall to steel roof</td>
<td>198</td>
</tr>
<tr>
<td>6.4.3</td>
<td>Connection of concrete wall to concrete roof</td>
<td>199</td>
</tr>
<tr>
<td>6.4.4</td>
<td>Pipes through a concrete roof</td>
<td>201</td>
</tr>
<tr>
<td>6.5</td>
<td>Functions of coatings and insulating layers attached to concrete</td>
<td>201</td>
</tr>
<tr>
<td>6.5.1</td>
<td>Gas-tightness</td>
<td>202</td>
</tr>
<tr>
<td>6.5.2</td>
<td>Vapour-tightness</td>
<td>202</td>
</tr>
<tr>
<td>6.5.3</td>
<td>Vapour-tight coating on the outside</td>
<td>203</td>
</tr>
<tr>
<td>6.5.4</td>
<td>Gas- and vapour-tight coating on the inside</td>
<td>203</td>
</tr>
<tr>
<td>6.5.5</td>
<td>Steel liner incorporated in the concrete structure</td>
<td>204</td>
</tr>
<tr>
<td>6.5.6</td>
<td>Insulating layers structurally connected to the inside of a concrete</td>
<td>204</td>
</tr>
<tr>
<td>6.5.7</td>
<td>Summary</td>
<td>206</td>
</tr>
<tr>
<td>7</td>
<td>GUIDELINES FOR TECHNICAL OPERATING REQUIREMENTS</td>
<td>209</td>
</tr>
<tr>
<td>7.1</td>
<td>Inspections and checks when the structure is in service</td>
<td>209</td>
</tr>
<tr>
<td>7.1.1</td>
<td>Wall structures</td>
<td>209</td>
</tr>
<tr>
<td>7.1.2</td>
<td>Gaps - Annular spaces</td>
<td>212</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>7.1.3 Roofs and wall-to-roof connections</td>
<td>213</td>
<td></td>
</tr>
<tr>
<td>7.1.4 Connections of pipes to tank roofs</td>
<td>213</td>
<td></td>
</tr>
<tr>
<td>7.1.5 Wall-to-base connections</td>
<td>214</td>
<td></td>
</tr>
<tr>
<td>7.1.6 Base structures</td>
<td>214</td>
<td></td>
</tr>
<tr>
<td>7.2 Commissioning and taking out of service</td>
<td>214</td>
<td></td>
</tr>
<tr>
<td>7.2.1 Commissioning</td>
<td>214</td>
<td></td>
</tr>
<tr>
<td>7.2.2 Taking out of service (shut-down)</td>
<td>216</td>
<td></td>
</tr>
<tr>
<td>7.2.3 Observations and repairs during maintenance phase</td>
<td>216</td>
<td></td>
</tr>
<tr>
<td>7.3 Operational requirements</td>
<td>216</td>
<td></td>
</tr>
<tr>
<td>8 CONSTRUCTIONAL ASPECTS AND ACTUAL STRUCTURES</td>
<td>219</td>
<td></td>
</tr>
<tr>
<td>8.1 Constructional and prestressing techniques</td>
<td>219</td>
<td></td>
</tr>
<tr>
<td>8.1.1 Methods of construction</td>
<td>219</td>
<td></td>
</tr>
<tr>
<td>8.1.2 Prestressing systems</td>
<td>221</td>
<td></td>
</tr>
<tr>
<td>8.1.3 Consequences of manner of execution</td>
<td>222</td>
<td></td>
</tr>
<tr>
<td>8.1.4 Constructing the concrete roof</td>
<td>223</td>
<td></td>
</tr>
<tr>
<td>8.2 Review of projects executed</td>
<td>223</td>
<td></td>
</tr>
<tr>
<td>8.3 Particulars of some projects executed</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>9 CONCLUDING REMARKS</td>
<td>233</td>
<td></td>
</tr>
<tr>
<td>10 REFERENCES</td>
<td>237</td>
<td></td>
</tr>
</tbody>
</table>
STATE OF THE ART REPORT "CONCRETE STORAGE VESSELS"

PREFACE

It was initially intended to issue this report as embodying the result of the work done by the sub-committee "Concrete Storage Vessels" of the C.P.R. (Committee for the Prevention of Disasters), of which sub-committee I am chairman.

During the sub-committee's discussions on the draft report which I had prepared it emerged that the form chosen for this report did not lend itself very well to finalizing, through such discussions, as a document that could be endorsed by all concerned. Among other reasons, this was so because many different disciplines are represented on the sub-committees, so that the concrete construction technology aspects, with which the report is mainly concerned, could not very suitably be discussed.

Besides, substantial portions of the draft were in fact discussed in the sub-committee, and comments offered in the course thereof have been taken into account as much as possible. At the same time, however, the author has made decisions on matters of formulation which are entirely his responsibility.

After due consideration I decided, despite the above-mentioned problems, to issue this compilation as a "State of the art Report". I came to this decision in view of the great need for more information on this very important subject. In addition, it ensures that the report can also serve to initiate discussion of these matters in a wider context.

Having regard to the rapid developments in this field, it must emphatically be pointed out that this report is not to be regarded as recording the results of a process of development that has meanwhile been completed. On the contrary, its contents are wide open to discussion, and considerable value will be attached to any significant comments that readers may wish to communicate to the author after a critical perusal of the
report. The fact that it was compiled in a short time (May 1978 - May 1979) was due mainly to the very substantial help I received from Messrs. Ir. J.F. Damen (D3BN Civil Engineers) and A.A. van der Vlist (Netherlands Cement Industries). In their capacity as an editorial committee they gave me valuable support, both by the revision of draft texts and by assisting in the discussion of various matters with those concerned.

I also wish to express my indebtedness to all those, especially in the field of concrete technology, who kindly subjected this report to a critical scrutiny and discussed it with the editorial committee.

My sincere thanks are furthermore due to Ir. C. van Amerongen, M.I.C.E., for his excellent English translation from the Dutch.

Furthermore, I am especially grateful to Mrs. I. Polderman for her excellent typing and lay-out of the report.

My student assistant Mr. W. Mol devoted much time and effort to organizing the compilation of the report, including the preparation of the drawings and diagrams. He, too, deserves my sincere gratitude.

I trust that this report will meet the expectations: to give information, as objectively as possible, concerning the possibilities offered by concrete structures for the safe storage of hazardous substances.

Delft, 31 August 1979

Prof. Dr. Ir. A.S.G. Bruggeling
SUMMARY

This "state of the art" report discusses the possibilities that concrete as a construction material can offer in making the storage of liquefied cooled hydrocarbons and other similar substances as safe as possible.

In order to highlight these possibilities, the relevant properties of concrete and of the steel used in concrete structures are first described. Of course, in this context, a good deal of attention is devoted to the behaviour of these materials at the low temperatures liable to occur in connection with the storage conditions envisaged here. It emerges that concrete as well as prestressing steel retain their strength properties at such temperatures. The toughness of prestressing steel undergoes only a slight decrease at extremely low temperatures. Under the action of explosions and impulse loads the concrete structure displays favourable behaviour, as has indeed long been known.

In those cases where, for structures of this kind, prestressed concrete is more particularly appropriate, it is explained what the characteristic differences between reinforced concrete and prestressed concrete structures are and why this last-mentioned material is so eminently suitable for the purpose.

The information given in this part of the report is intended chiefly for readers who are not familiar with concrete structures. In order to give them some insight into the scope offered by such structures, the next part of the report describes a series of constructional forms and their possibilities, using a simple system of coding to indicate them. They comprise structures ranging from so-called safety walls built around existing tanks to fully integrated tank systems in which the constituent materials steel, insulation and concrete co-operate as efficiently as possible. In this way the reader is given some idea of the various possibilities and is thus provided with a basis enabling him to weigh the pros and cons of different solutions.
The report is concerned mainly with above-ground tanks. It also devotes attention to tanks installed wholly or partly below ground level and tanks banked externally with earth, and it indicates the various consequences with regard to design and construction. Of major importance in the design of tanks for the storage of liquefied cooled hydrocarbons and comparable other substances are the design loads and load factors to be adopted.

It is of course not possible fully to quantify the loads, more particularly the so-called special loads. It has nevertheless been endeavoured to give guide values for these loads and also for the load factors, so that suitable approximate estimates can be made.

The final chapters give information on some important structural details of concrete tanks and on the type and location of features such as vapour-tight layers, coatings, etc.

As for the actual construction procedures for the concrete structures described here, sufficient information is provided to give the non-expert on concrete constructional engineering some idea of the possibilities.

A separate chapter describes how concrete structures should be inspected and on what aspects the inspections should more particularly concentrate.

The list of literature references given at the end of the report has been so compiled that the publications relating to the various main subject matters are grouped together as far as possible.
Samenvatting

In dit State-of-the-Art report zijn de mogelijkheden besproken, welke beton kan bieden om de opslag van tot vloeistof gekoelde koolwaterstoffen en soortgelijke stoffen zo veilig mogelijk te doen zijn. Teneinde deze mogelijkheden duidelijk te maken, worden eerst de relevante eigenschappen van beton en het in betonconstructies voorkomende staal besproken. Uiteraard is daarbij bijzondere aandacht besteed aan het gedrag van deze materialen bij de lage temperaturen, waarover bij de hier bedoelde opslag sprake kan zijn. Daardoor wordt het duidelijk dat onder lage temperaturen zowel beton als voorspanstaal tenminste zijn sterkte behoudt. De taaiheid van het voorspanstaal neemt onder extreem lage temperaturen slechts weinig af. Onder de invloed van explosies en impulsen vertoont de betonconstructie, zoals reeds lang bekend, een gunstig gedrag.

Waar in dit soort constructies in het bijzonder voorgespannen beton in aanmerking komt, wordt duidelijk gemaakt wat de karakteristieke verschillen tussen gewapend- en voorgespannen betonconstructies zijn en op grond van welke overwegingen voorgespannen beton in dit opzicht het constructiemateriaal is dat bij uitstek voldoet.

De in dit deel van het rapport gegeven informatie is in hoofdzaak bedoeld voor degenen, die niet vertrouwd zijn met betonconstructies. Teneinde inzicht te geven in de mogelijkheden van betonconstructies wordt dan in een volgend deel via een eenvoudig coderingssysteem een trits van constructievormen aangeduid en hun mogelijkheden besproken. Het gaat daarbij via de zogenaamde veiligheidswanden, die om reeds bestaande tanks zijn aangebracht, tot geïntegreerde constructies waarin de verschillende materialen staal, isolatie en beton op een zo optimaal mogelijke wijze samenwerken. Daardoor wordt een beeld gegeven van de verschillende mogelijkheden, waardoor een basis is geschapen op grond waarvan diverse oplossingen t.o.v. elkaar kunnen worden afgewogen.

Deze handeling spitst zich toe op ag. bovengrondse tanks. Van de geheel of gedeeltelijk ondergrondse dan wel aangeaarde tanks worden de verschillende consequenties t.a.v. ontwerp en uitvoering aangeduid. Van grote betekenis voor het ontwerp van tanks voor de opslag van
tot vloeistof gekoelde koolwaterstoffen e.d. wordt geacht de in rekening te brengen belastingen en de daarbij aan te houden belastingfactoren.

Het is uiteraard niet mogelijk om de belastingen - met name de bijzondere belastingen - volledig te kwantificeren. Getracht is daarvoor wel richtwaarden te geven en ook voor de belastingfactoren, zodat op grond daarvan e.e.a. kan worden afgeschat.

Tenslotte is in de laatste hoofdstukken informatie verstrekt m.b.t. enige belangrijke constructiedetails van betonnen tanks en de aard en de plaats van dambichte lagen, coatings, enz.

Over de wijze van bouwen van de hier besproken betonconstructies wordt zoveel informatie verstrekt als noodzakelijk is om de niet-betondeskundige een idee te geven van de mogelijkheden.

In een apart hoofdstuk is aangegeven hoe gerealiseerde betonconstructies dienen te worden geïnspecteerd en waarop deze inspecties zich dienen te richten.

De aan het eind van dit rapport opgenomen literatuurinformatie is zodanig opgesteld dat literatuur, betrekking hebbend op de verschillende aandachtsvelden, zoveel mogelijk bij elkaar is gebracht.

De oorspronkelijke uitgave van dit rapport in de Nederlandse taal is uitgegeven door Bouwresearch.

Deze Engelse uitgave wijkt slechts op ondergeschikte punten iets af van het Nederlandse stuk.
INTRODUCTION

1 Objective of this report

The objective of this "state of the art" report can be defined as follows:

- To indicate the possibilities that special concrete structures can offer in contributing to safety in the bulk storage under near-atmospheric pressure (i.e., practically unpressurized) of cooled hydrocarbons and other substances with comparable properties.

Obviously, this report is primarily geared to conditions existing in the Netherlands, but in view of the many points of similarity, particularly in the subject field considered here, the report will be applicable, with hardly any amendments, to those existing in other European countries as well. For the other continents of the world this report could likewise be serviceable if it were supplemented in respect of a few specific circumstances, e.g., the effect of earthquakes, and the possibilities offered by tanks installed entirely under ground.

Gases and liquids with which this report is concerned

Various gases - especially hydrocarbons, but others too - are nowadays stored preferably in liquid form. For this purpose they are cooled to their boiling point, which for most gases is below 0 °C. Gases can be liquefied also by raising the pressure, but the present report is not concerned with such storage under pressure.

Liquefaction by cooling is attended by a sometimes very considerable decrease in volume (e.g., to about 1/600 of the original volume in the case of natural gas). As a result, the storage space can be reduced in the same ratio. However, if the gas in question is a "hazardous substance", which is usually the case, this reduction in volume also means that the potential danger is liable to be concentrated to the same extent. Hence extra safety arrangements are needed - more than are required for the storage of the original gas.
Gases thus cooled to the liquid state can be stored under very nearly atmospheric pressure (i.e., practically unpressurized), as they have not been liquefied by raising their pressure. For this reason, too, the storage vessel need not be able to resist (high) gas pressures, as is necessary for storage under pressure. The storage vessel must, however, be insulated in order to be able to maintain the desired (low) temperature.

Despite the insulation, some heat transfer will take place through the walls and bottom of the storage vessel, so that evaporation (or "boil-off") of some liquid will occur as a result and a certain excess pressure (i.e., above-atmospheric pressure) of the gas in the vessel will develop. As a rule, this excess pressure is fairly low, up to about 0.15 bar, depending on the nature of the substance stored and on the technical arrangements for limiting the gas pressure. The amount of boil-off that can be regarded as economically acceptable will be the criterion for deciding how effectively the vessel should be insulated.

The bulk storage of liquefied cooled hydrocarbons and comparable other substances at near-atmospheric pressure is known as cryogenic storage, but will, for simplicity of terminology, be referred to as "unpressurized cooled storage" in this report.

Hydrocarbons are compounds of the chemical elements carbon (C) and hydrogen (H). As a rule, a distinction is drawn between saturated and unsaturated hydrocarbons. The saturated hydrocarbons, or alkanes, have the general formula \( \text{C}_n\text{H}_{2n+2} \) (as exemplified by methane \( \text{CH}_4 \) and ethane \( \text{C}_2\text{H}_6 \)). The unsaturated hydrocarbons include the alkenes \( (\text{C}_n\text{H}_{2n}) \) (e.g., ethene or ethylene \( \text{C}_2\text{H}_4 \) and propene or propylene \( \text{C}_3\text{H}_6 \)). Other unsaturated hydrocarbons are the alkynes and the alkadienes (both with the general formula \( \text{C}_n\text{H}_{2n-2} \), e.g., ethyne \( \text{C}_2\text{H}_2 \) and butadiene \( \text{C}_4\text{H}_6 \)).

Table 1 gives an alphabetical list of a number of hydrocarbons, both saturated and unsaturated, which are suitable for unpressurized cooled storage. It also includes three so-called hydrocarbon derivatives

\* 1 bar = 0.1 N/mm² = approx. 1 atmosphere

1000 mbar = 1 bar
(methanal or formaldehyde, methyl chloride, vinyl chloride) because they possess comparable properties in this respect. Furthermore, the table lists seven other gases which can likewise be stored under unpressurized cooled conditions (ammonia, chlorine, carbon monoxide, nitrogen, hydrogen, oxygen and hydrogen sulphide).

Finally, the table includes acrylonitrile and naphtha. Although such liquids are not stored under cooled conditions, they certainly belong to the category of "hazardous substances".

The principal characteristic properties of the gases or liquids listed in the table are likewise indicated there: density, boiling point, flash point, self-ignition temperature and the flammability limits*.

The density (in kg/m³) is the mass (in kg) of 1 m³ of liquid, more particularly the mass of 1 m³ of liquid (at its boiling point) obtained by the cooling of gas. (Density, as conceived here, used to be called "specific gravity").

The boiling point is the temperature (in °C) at which the whole of the liquid boils under atmospheric pressure, i.e., evaporated. In the case of unpressurized cooled storage the storage temperature is equal to the boiling point.

The flash point is the lowest temperature (in °C) at which the liquid gives off sufficient flammable vapour to undergo ignition when ignited.

* The values given in Table 1 have mostly been obtained from [6-2] and furthermore from a few other sources. There is some variation in the values stated for these properties in the literature. This applies more particularly to the "boiling points" — probably because a lower temperature than the theoretical value is adopted, for reasons of safety, in the design of storage structures. Besides, the presence of contaminants is liable to lower the boiling point. The temperatures (temperature levels) are here indicated in degrees Centigrade. This is not only permissible, but conversion to Kelvin temperatures could give rise to errors in rounding-off.
<table>
<thead>
<tr>
<th>gas or liquid</th>
<th>density (as liquid) (kg/m³)</th>
<th>boiling point (°C)</th>
<th>flash point (°C)</th>
<th>self-ignition temperature (°C)</th>
<th>limits of flammability (per cent by vol.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>acetylene - see ethyne*</td>
<td>600</td>
<td>-1</td>
<td>-138</td>
<td>365</td>
<td>1.5...8.5</td>
</tr>
<tr>
<td>butane C₄H₁₀</td>
<td>650</td>
<td>-4</td>
<td>85</td>
<td>415</td>
<td>1.1...12.5</td>
</tr>
<tr>
<td>butadiene C₄H₆</td>
<td>630</td>
<td>-6</td>
<td>-185</td>
<td>&gt;300</td>
<td>1.6...10</td>
</tr>
<tr>
<td>butene C₄H₈</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>butylene - see butene</td>
<td>547</td>
<td>-89</td>
<td>&lt;-89</td>
<td>515</td>
<td>3.0...13.5</td>
</tr>
<tr>
<td>ethane C₂H₆</td>
<td>570</td>
<td>-104</td>
<td>&lt;-104</td>
<td>425</td>
<td>2.7...34</td>
</tr>
<tr>
<td>ethene C₂H₄</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ethylene - see ethene</td>
<td>620</td>
<td>-84</td>
<td>&lt;-84</td>
<td>305</td>
<td>1.5...100</td>
</tr>
<tr>
<td>ethyne* C₂H₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>formaldehyde - see methanal</td>
<td>425</td>
<td>-161</td>
<td>&lt;-161</td>
<td>595</td>
<td>5...15</td>
</tr>
<tr>
<td>methane CH₄</td>
<td>770</td>
<td>-19</td>
<td>-19</td>
<td>430</td>
<td>7...73</td>
</tr>
<tr>
<td>methyl chloride CH₃Cl</td>
<td>940</td>
<td>-24</td>
<td>&lt;-24</td>
<td>625</td>
<td>10.7...17.2</td>
</tr>
<tr>
<td>propane C₃H₈</td>
<td>582</td>
<td>-42</td>
<td>-187</td>
<td>470</td>
<td>2.1...9.5</td>
</tr>
<tr>
<td>propene C₃H₆</td>
<td>610</td>
<td>-48</td>
<td>&lt;-48</td>
<td>455</td>
<td>2...11.7</td>
</tr>
<tr>
<td>propylene - see propene</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vinyl chloride C₃H₅Cl</td>
<td>930</td>
<td>-14</td>
<td>-77</td>
<td>470</td>
<td>4...29</td>
</tr>
<tr>
<td>ammonia NH₃</td>
<td>640</td>
<td>-33</td>
<td>&lt;-33</td>
<td>630</td>
<td>15...28</td>
</tr>
<tr>
<td>chlorine Cl₂</td>
<td>1560</td>
<td>-34,5 (not applicable, incombustible)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>carbon monoxide CO</td>
<td>791</td>
<td>-191</td>
<td>&lt;-191</td>
<td>605</td>
<td>12.5...74.2</td>
</tr>
<tr>
<td>nitrogen N₂</td>
<td>808</td>
<td>-196</td>
<td>(not applicable, incombustible)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hydrogen H₂</td>
<td>?</td>
<td>-253</td>
<td>-240</td>
<td>560</td>
<td>4.0...75.6</td>
</tr>
<tr>
<td>oxygen O₂</td>
<td>1141</td>
<td>-183</td>
<td>(not applicable?)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hydrogen sulphide H₂S</td>
<td>914</td>
<td>-60</td>
<td>&lt;-60</td>
<td>270</td>
<td>4.3...46</td>
</tr>
<tr>
<td>acrylonitrile C₃H₃N</td>
<td>?</td>
<td>+77</td>
<td>-5</td>
<td>480</td>
<td>3...17</td>
</tr>
<tr>
<td>naphtha C₆H₁₄</td>
<td>660</td>
<td>+60</td>
<td>-20</td>
<td>240</td>
<td>1.2...7.4</td>
</tr>
<tr>
<td>(C₆H₁₄, C₇H₁₆ et al) C₇H₁₆</td>
<td>690</td>
<td>+100</td>
<td>-4</td>
<td>215</td>
<td>1.1...6.7</td>
</tr>
</tbody>
</table>

* Acetylene (ethyne) is theoretically, but not practically, suitable for unpressurized cooled storage. This gas can be liquefied by cooling it to -83.6 °C at atmospheric pressure. However, the possibility that will solidify ("crystallize") can then not be ruled out. The triple point is at -81.8 °C and a pressure of 1.29 atm.

Natural gas (LNG) consists of 80 - 90% (by vol.) of methane. Petroleum gas (LPG) consists mostly of propane and/or butane and furthermore of propene and/or butene.
The self-ignition temperature is the lowest temperature (in °C) at which the gas will ignite spontaneously, i.e., without external ignition.

The explosion limits or limits of flammability are the percentages of gas (in % by volume) in a gas/air mixture which constitute the limits of the so-called explosive range. If the percentage of gas is below the lower limit of this range, the mixture contains too little gas to be ignitable; it therefore cannot explode. If the percentage is above the upper limit, the gas concentration in the mixture is too high for ignition, so that there is then likewise no risk of explosion.

The rate at which the chemical reaction between the gas and the atmospheric oxygen (serving as the oxidant) takes place is considerably lower according as the gas percentage in the mixture is closer to the upper or the lower limit of flammability. At these limits there is in fact no question of an "explosion", but merely of combustion with a relatively low flame velocity. Hence the terms lower limit of flammability and upper limit of flammability are more accurate than lower and upper explosion limits.

A wide explosive range is generally indicative of a very hazardous substance, because in that case there is a considerable risk of the formation of a combustible or indeed an explosive gas/air mixture. The risk of fire or explosion is higher according as the lower limit of flammability is lower.

The gases and liquids listed in Table 1 are classed as "hazardous substances" mainly on account of their combustibility and potential explosiveness. Gases liquefied by cooling may moreover present a hazard because of their low temperatures. Besides, some gases and liquids are toxic or harmful in other ways.

The hydrocarbons and their derivatives, as listed in Table 1, are not chemically aggressive to concrete. They may therefore be stored in direct contact with concrete, unless they contain contaminants.
or additives which do attack concrete. The same can be said of the other gases and liquids mentioned in the table, with the exception of hydrogen sulphide, which is (feebly) aggressive to concrete.

Chlorine ions do not attack concrete, but they can be harmful to reinforcing steel (in reinforced concrete) and to prestressing steel (in prestressed concrete). For this reason the storage of chlorine requires special precautions to protect reinforcing steel and/or prestressing steel from attack.

In general, the various substances are allowed to come into contact with concrete if it is certain that they will not attack the concrete and the reinforcing or prestressing steel embedded in it. The presence of contaminants or additives may be the deciding factor in this respect and therefore should be checked. With some substances (such as hydrogen sulphide) it cannot be ruled out that their aggressiveness will fully develop only when the storage vessel has been emptied (e.g., for maintenance).

1.3 Subdivision of this report

In view of the stated objective (see 1.1), this report in any case comprises the following three sections:

- Supplying information on relevant properties of concrete structures and their constituent materials. This has been done in such a manner that those who – for example, at managerial level – are required to indicate adequate measures relating to "unpressurized cooled storage" will be able to form an opinion on the possibilities of concrete structures in this field of application.

- Describing recent developments in concrete structures in this field. In connection with this, a critical assessment of structural possibilities and their details is given. With regard to the possibilities of application it is indicated which solutions are to be preferred in particular cases, and why.

- Referring the reader to standards, codes, recommendations, etc. existing in the Netherlands or in other countries and relating to:
(a) the structural design loads; (b) the design and analysis of the structures envisaged here; (c) the detailing of such structures. With regard to the (special) loads not covered by existing codes, etc. it is indicated how such loads can be determined and - if possible - what order of magnitude they have.

The report is so compiled that it provides information for a wide and, at the same time, varied circle of interested parties. It comprises ten chapters, of which the first four contain mainly "general information", while the other six supply mainly "technical information".

Chapter 2 reviews the problems that may arise in connection with "unpressurized cooled storage". It is more particularly concerned with the consequences of these undesirable events, since it is these consequences that may ultimately necessitate structural or other arrangements.

Chapter 3 deals with the properties of concrete and concrete structures under the ordinary as well as the special loads that may occur with "unpressurized cooled storage".

The possible storage systems and structural shapes in concrete are described in Chapter 4. The description given in it approximately reflects the course of developments in the field of "unpressurized cooled storage".

The next six chapters are primarily intended for designers and detailers in this special field of concrete structural engineering. It gives systematic and full information on what is at present known concerning the design and detailing of concrete structures for the storage of gases liquefied by cooling.

Following the example of Netherlands Standard NEN 3850 ("Technical principles for the design of building structures - TGB 1972 - General part and loads") [1-1], in this report the loads under normal operating conditions are called "ordinary" loads, and those under abnormal conditions are called "special" loads.
Chapter 5 is concerned with the loads to be taken into account in the design calculations - not only the "ordinary" loads, but also the "special" ones (see note on page 21) which occur under other than normal conditions.

Chapter 6 deals with the principal structural details, such as the wall-to-bottom and wall-to-roof connections and the connection(s) with the foundation.

Guidelines for the operational requirements with regard to the inspection and observation of the structure and the structural details, the commissioning and shutting-down of storage installations, etc.

Chapter 8 considers a number of constructional aspects and presents a review of projects executed in the Netherlands and abroad, with concrete as the structural material, some of which are described in greater detail.

The report ends with a summary and some conclusions (Chapter 9) and a comprehensive list of literature references (Chapter 10). This final chapter is intended more particularly for those who wish to go more deeply into the extensive subject of "unpressurized cooled storage" in general and into the possible applications of concrete in connection with it in particular.

1.4 Limitations of this report

This report is based on conceptions current in mid-1979, which naturally implies a limitation. Developments in the subject under consideration are bound to continue. Hence this report will in due course have to be "adjusted", as soon as those developments necessitate it. The present first edition of this "state of the art" report provides a suitable starting point for such progressive adjustment.

Besides, the report now already constitutes a document providing a basis for discussing the possibilities of concrete structures for
"unpressurized cooled storage" in a wider circle. The author, for his part, will be grateful for comments, supplementary information and suggestions for the amendment of the report, so that it can be brought up to date and published.

In view of its objective, the report is ultimately concerned with safety in connection with "unpressurized cooled storage". That is why all kinds of safety aspects are considered. These aspects are, however, merely described and examined, but not further evaluated, as that would be outside the scope of this report.
Safety wall around
Ammonia tank - DSM - Geleen - Netherlands
Capacity 25,000 m³
Construction with climbing formwork
2 ASPECTS OF "UNPRESSURIZED COOLED STORAGE"

2.1 Introduction

Special tanks are used for the storage of large quantities of liquefied cooled hydrocarbons and other substances with comparable properties (see Table 1). The requirements applicable to such tank structures relate to:

a. structural strength (load capacity);
b. sealing (liquid, gas);
c. insulation;
d. protection against special influences.

Such tanks should of course fulfill the structural requirements applicable to them under normal operating conditions. These requirements are bound up with the "ordinary" loads, more particularly the (hydrostatic) pressure exerted by the stored liquid, with liquid-tightness and gas-tightness, and with thermal insulation in order greatly to restrict the evaporation that would otherwise occur on account of the low temperature at which the liquid is stored.

At the same time, however, the storage structures should be so designed that they will continue to function even if problem conditions arise which cause "special" loads. Otherwise such undesirable events are liable to cause damage and loss, both materially and to people.

Possible causes of such events are: structural engineering defects, fault conditions, erroneous actions (human fallibility), and various extreme external influences such as fire, explosion, sabotage and natural phenomena.

The following systematic treatment of possible problems associated with "unpressurized cooled storage" (see 2.3) is based on (fortunately: a limited number of) instances of experience in actual practice, on theoretical considerations, and on the analysis and extrapolation of problems occurring in connection with similar structures for other purposes or of smaller size.
Each possible problem constitutes in fact a risk for the storage plant itself and usually also for its surroundings, since damage may be caused to installations, buildings, etc., as well as injury to persons working in the storage plant or present in the vicinity thereof.

Although this report is ultimately concerned with the safety of "unpressurized cooled storage", it will not enter into an analysis of the risks envisaged here: the probability of the events associated with them and the extent of the damage resulting from them. In general, the probability of the occurrence of an undesirable event will be fairly low, but on account of the nature of the stored liquid (combustible and explosive, low temperature, sometimes toxic) the damage caused by it may be considerable.

Furthermore, this report will devote little or no attention to possible safety precautions applicable to the actual installation, e.g., in the form of double-seated valves, interlock systems, blow-off valves to prevent gas overpressure, and the admission of confining gas to prevent underpressure. Such precautions can, however, never be regarded as completely eliminating all risks. It is therefore necessary to take account of undesirable events due to failure of one or more safety devices.

Since possible problems associated with "unpressurized cooled storage" are partly bound up with the storage system, this chapter first gives a general description of the various systems (see 2.2), outlining only the respective principles on which they are based. (The storage systems and the possible forms of construction in concrete are fully described in Chapter 4).

2.2 Storage systems

2.2.1 Single-walled tank

The single-walled tank system is generally used for the storage of liquids such as water and oils, but is sometimes also used for the
storage of liquefied cooled gases. A tank of this kind may develop leakage, be damaged and may even collapse. Despite all sorts of precautions, the risk of these things happening can never be completely ruled out. Hence the consequences of such eventualities must be taken into account: the escape of liquid which, besides being (very) cold, is frequently combustible in character, especially after evaporation has occurred.

Particularly with combustible liquids it is necessary to limit the containment area into which the liquid escapes. This has traditionally been achieved by surrounding the tank with an earth bank or a wall so as to form a containment enclosure or catch basin (fig. 1), which may be rectangular, square or circular.

![Fig. 1. Single-walled tank (schematic) provided with insulation; enclosed within an earth bank (left) or a wall (right)](image)

A protective arrangement of this kind (wall or earth bank) will protect the adjacent installations, buildings, etc. from "inundation" and may limit the possible contamination of surface water or ground water. The advantage of a wall, usually built of concrete, over an earth bank is that the external dimensions of the catch
basin will be smaller, so that individual tanks can be spaced closer to one another (though the minimum spacing of tanks may depend also on other factors).

As a rule, the storage temperature of liquefied cooled gases is equal to the boiling point of those gases - usually below 0 °C (see Table 1, page 18). In order to restrict evaporation, the storage tank must be provided with insulation (fig. 1). The insulating material will, as a rule, be applied to the outside of the tank, in which case some arrangement will be necessary for enclosing or protecting this materials. Any such arrangement is not intended to perform a liquid-retaining function in an emergency. Hence this kind of tank is likewise surrounded by a wall or bank (fig. 1) to act as a second line of defence in the event of escape of liquid.

If the temperature of the stored liquid is lower than about -50 °C, however, the provision of an enclosure for the insulation will lead to the construction of a double-walled tank.

2.2.2 Double-walled tank

A double-walled tank comprises an inner tank ("primary tank") and an outer tank, with insulation in between (fig. 2).

![Double-walled tank diagram](image)

**Fig. 2. Double-walled tank (schematic) provided with a second liquid-retaining structure; enclosed within an earth bank (left) or a wall (right)**
The outer tank can in principle be designed to act as a second liquid-retaining structure which can, if necessary, perform the function normally performed by the inner tank. However, if the outer and the inner tank are not equivalent in this respect, the second line of defence against the escape of liquid is here, too, provided by an earth bank or a wall (fig. 2).

Particularly if the outer tank is so designed as to be able to perform the function of the inner tank is an emergency, a double-walled tank will to some extent resemble a so-called integrated tank (see 2.2.4).

2.2.3 Safety wall

A single-walled or a double-walled tank will in many cases have to be able to withstand external influences such as fire, explosion, sabotage and natural phenomena. A tank wall can, in principle, be designed to meet such requirements. Alternatively, the tank will be provided with an extra protection in the form of a surrounding safety wall, which is usually constructed of concrete and is installed at some distance from the tank (fig. 3).

Fig. 3. Double-walled tank provided with a safety wall (schematic); narrow gap between tank and safety wall (left) or wide gap (right)
Obviously, this wall can suitably be designed to act as a second liquid-retaining enclosure, so that no earth bank or wall to form a catch basin is then required. A safety wall can be banked with earth on the outside, thus further improving the protection it gives against all manner of external influences.

The space between the tank wall and the safety wall is here referred to as the "gap". There are various drawbacks associated with the gap (see "Gap problems", p. 105). Partly for this reason further development has been towards the so-called integrated tank, a form of construction which has no "gap", also called annular space.

2.2.4 Integrated tank

The integrated tank is the result of a development process aimed at improving the safety of storage structures. This can be achieved by using an optimum combination of the materials steel, concrete and insulation in such a way that each material is utilized only in that part of the structure where the material most advantageously performs its function.

Accordingly, in this report an integrated tank is conceived as a combination of the materials steel, concrete and insulation, together performing the functions that are required of the tank with regard to strength, liquid- and gas-tightness, insulation and protection.

---

Fig. 4. Integrated tank comprising an inner and an outer tank (schematic); further integration results in a single-walled tank
In its simplest form an integrated tank resembles a double-walled tank of which the outer tank is so designed as to be able to perform the function of the inner tank, should circumstances require that. A characteristic feature is more particularly that this outer tank also functions as a safety wall (fig. 4). Examples of this constructional principle are double-walled tanks comprising a steel inner tank and a concrete outer tank, and double-walled concrete tanks. Developments in this field have led to a single-walled concrete tank of such design that it combines the functions of inner and outer tank as well as of safety wall. Depending on its location, a tank structure of this kind may be combined with a safety wall.

2.2.5 Underground and/or earth-protected tanks

Storage tanks are mostly built as above-ground structures, but in principle they can also be installed underground (wholly or partly), more particularly in order to give them greater protection against all manner of external influences (fig. 5).

---

alternative underground tank

= insulation

Fig. 5. Underground tank (schematic)

A tank which is entirely below ground level does not, of course, require a second liquid-retaining enclosure nor a safety wall. This solution does, however, involve a number of structural problems (see 4.11) which can perhaps be overcome only by installing the tank in a "pit".
Alternatively, an above-ground tank can be banked with earth on the outside, over the full height of the tank wall or over a part of it, the object likewise being to give the tank better protection against external influences of all kinds (fig. 6).

Fig. 6. Tank banked with earth (schematic)

If the external earth bank comprises the full height of the tank, a safety wall is unnecessary. However, this solution also involves quite a few structural problems (see 4.11), such as those due to the weight of the earth backfill and to the penetration of cold into this earth. Similar problems are likely to be encountered in a case where earth is banked against a safety wall, though here they are in principle easier to cope with.

2.3 Possible problems

In connection with unpressurized cooled storage - as envisaged in this report - an "undesirable event" will more particularly involve the escape of gas and, especially, the escape of liquid which evaporates to gas. When that occurs, a gas/air mixture is formed which, for the majority of these stored substances, is liable to be combustible and even explosive. Besides, some gases and liquids are toxic or harmful in other ways. Liquefied cooled gases may moreover constitute a hazard because of their low temperature alone.
For convenience of presentation the undesirable events are subdivided, according to origin, into those due to "internal causes" (arising from process engineering or structural factors) (see 2.3.1) and those due to "external causes" (see 2.3.2.).

2.3.1 Internal causes

"Events of internal origin" arise:

a. from the process, e.g., in consequence of failure of the installation (including the safety devices), mistakes (human fallibility), etc. (see 2.3.1.1 to 2.3.1.3);

b. from the structure, e.g., in consequence of defects and possible failure of the storage tank (see 2.3.1.4).

2.3.1.1 Gas overpressure

Evaporation occurs at the surface of a gas liquefied by cooling. The thermal insulation of the tank ensures that the rate of evaporation of "boil-off" is low. The boil-off gas produces a certain excess pressure, which can, however, be limited by discharging this gas. Blow-off valves and other such devices can provide additional safeguards against excessively high pressure build-up.

A small excess pressure, of the order of 0.15 bar, is generally regarded as permissible. The structure, especially the roof, is designed to withstand this pressure.

A high rate of evaporation, i.e., associated with increasingly high gas pressure, may occur in consequence of sudden development of instability of the contents of the tank. This can happen if the liquid in the tank is "stratified", i.e., is present in two or more layers differing in density and/or temperature. As a result of evaporation occurring at the surface of the upper (lightest) layer, the density of this layer may become greater than that of the underlying layer or layers. If that happens, displacement of the layers of liquid in relation to one another may occur under exceptional conditions:
the liquid which has thus become heavier suddenly sinks, causing the underlying lighter liquid to rise to the surface ("roll-over"). During this turbulent motion, intense evaporation takes place. A roll-over certainly imposes an additional load on the wall of the tank, but there is no known instance where this has hitherto resulted in structural failure.

Stratification can be counteracted by filling the tank both at the top and near the bottom. The rate of filling or emptying also has an effect on the occurrence of stratification. (In this respect there is considerable difference between storage tanks for terminals and those for so-called peak-shaving installations). Circulating pumps and other such aids can ensure proper mixing of the liquid in good time and thus provide an extra safeguard in this respect.

The various safety devices may, however, fail to perform their duty, so that the gas pressure becomes too high (overpressure). This in turn may cause failure of the weakest part or component of the structure. In most cases this means that the roof of the tank totally or partly collapses. When that happens, gas will escape from the top of the tank. Besides, considerable evaporation will occur, causing even more gas to escape. Escape of gas will also occur in the event of failure of pipes, joints, valves, etc. mounted on or in the roof.

2.3.1.2 Gas underpressure

A certain negative pressure may develop in the tank as a result of too-rapid discharge of the boil-off gas (see 2.3.1.1), as a result of a change in atmospheric pressure and especially as a result of too-rapid discharge of liquid (emptying). This pressure can be kept within acceptable limits by the introduction of a confining gas. The structure, more particularly the roof, is designed to withstand the permissible value of the negative pressure (of the order of 5 mbar).

The various safety arrangements may fail, however, thus allowing the negative pressure to become too high (underpressure). This is
liable more particularly to cause damage to the roof and even bring about its total or partial collapse. The consequences may then be similar to those already described above (see 2.3.1.1).

2.3.1.3 Overfilling

Gas overpressure (see 2.3.1.1) may also occur if the tank is overfilled as a result of human error or malfunction of safety devices. The tank structure should be designed to withstand this additional loading due to an abnormally high level of liquid. As a rule, this extra margin of strength will be required only for the wall, not the roof, at least if the tank can overflow without exertion of liquid pressure on the roof.

In most storage systems overflow due to overfilling will cause some of the liquid pouring over the edge of the wall to penetrate into the insulation, thus impairing its effectiveness. In that case considerable evaporation will occur in the insulation cavity and especially also in the tank, so that the excess pressure of the gas becomes too high (see 2.3.1.1). Furthermore, the cold liquid may come into contact with parts of the installation which are not resistant to it.

2.3.1.4 Errors in design, construction and materials

The structure of a storage tank may develop defects (leakage, cracking, even total or partial failure) in consequence of errors in design, in construction or in the materials employed. By the introduction of so-called safety factors or load factors, which is commonly done in normal design practice, it is possible to prevent the cumulation of adverse influences from resulting in undesirable events. For the analysis of the structure it is necessary to know the behaviour of the structural materials at low temperatures, etc. A close check on workmanship will have to be maintained during execution of the job.
Storage tanks have the advantage that they can be subjected to test loading. For this purpose they can be filled with a liquid such as water. A cooling test is another possibility: in that case a liquefied gas is evaporated in the tank in such a way that the temperature gradually falls (known as a "cooldown operation"). With the aid of such test loads possible flaws or defects in the tank wall, the insulation, etc. can be detected. Special monitoring techniques are available for this purpose.

Steel tanks intended for unpressurized cooled storage are constructed of steel plate of a grade which differs from ordinary carbon steel in having a higher notch toughness and cracking resistance at low temperatures than ordinary carbon steel. Despite the above-mentioned possibilities and precautions in connection with the design, construction and choice of material for such tanks, the realistic designer will, even so, not rule out the possibility of the occurrence of the so-called "zipping effect" - a phenomenon characterized by very rapid ripping-open of the tank wall. Accordingly, in this report the failure of a storage tank is treated as an undesirable event of internal origin. Particularly if this zipping effect occurs, a large quantity of cooled liquid will pour out in one rush, which is of course liable to have serious consequences.

2.3.2 External causes

"Events of external origin" arise from causes located outside the storage tank and giving rise to the escape of gas or the outflow of liquid.

2.3.2.1 Fire in the vicinity

A storage tank may be damaged by radiant heat in the event of an outbreak of fire in an adjacent tank, installation, etc. As a result, the contents of the tank may catch fire, whether or not after liquid has escaped from the tank.
The distance between the tank and any potential source of fire in the vicinity can be chosen so large that the intensity of the heat radiation at the tank concerned is limited to permissible values.

Besides, the structure (i.e., the storage tank or the safety wall) can be protected from this radiant heat by providing it with a sprinkler system on the outside. In practice, however, the possibility that such a system may become defective under the influence of the heat will be taken into account. The desired protection can alternatively be obtained by the application of an external layer of insulating material (e.g., perlite-mortar).

2.3.2.2 Explosion in the vicinity

A storage tank may be damaged by a shock wave in the event of an explosion in an adjacent tank, installation, etc. Such damage may result in an outflow of liquid.

The effect of an explosion can be limited to that of normal loads by adequately increasing the distance between the tank in question and any possible source of explosion in the vicinity. However, in order to cope with an explosion of some magnitude, this method of protection will necessitate unreasonably large distances between the various tanks and installations. As a rule, therefore, the total structure (including the foundation) is designed to withstand the effects of a possible nearby explosion.

During an explosion there will occur a pressure load - sometimes increased by "reflection" - which exerts a horizontal force upon the structure (risk of overturning!). Directly after the passage of the pressure wave there often occurs a negative pressure which the structure must likewise be designed to withstand.

2.3.2.3 Fragments hurled away

A storage tank may be damaged by being hit by flying fragments, pieces of equipment, etc. which are hurled away from a nearby
explosion. So much energy may be concentrated in such fragments that they will not only cause damage but also an outbreak of fire. The structure (storage tank, safety wall, etc.) should therefore be designed to withstand the effects of such "hits".

2.3.2.4 Sabotage

A storage tank can be damaged by sabotage activities. In this context the use of bullets, explosives, anti-tank rockets and even (light) mortar shells must be reckoned with. It may be desirable to design the structure (storage tank, safety wall, etc.) so as to survive the effects of hits by such missiles or destructive agents. With regard to this it is necessary to distinguish between bullets, high-explosive shells, etc. and so-called hollow-charges, which can penetrate to very considerable depths.

2.3.2.5 Aircraft, etc.

In the neighbourhood of airports, especially in the incoming and outgoing flight paths, it may be necessary to reckon with the possibility of crashing aircraft and fragments hurled away from such aircraft. The "hardware", especially the engine, is more particularly important from this point of view. Possible damage due to stray bullets, rockets, etc. may have to be considered as a hazard in the neighbourhood of military target practice areas for land, air or naval forces.

2.3.2.6 Natural phenomena

For the sake of completeness it is, finally, necessary to draw attention to natural phenomena and disasters such as lightning, static electricity, hurricanes, floods and earthquakes.

2.4 Undesirable consequences

Undesirable events, of internal or external origin (see 2.3.1 and 2.3.2) may result in the escape of gas and/or the outflow of liquid.
The liquid that flows from a damaged tank will evaporate to from
gas, a process which especially at first occurs very rapidly
("initial flash") because the liquid, generally at low temperature,
suddenly enters warmer surroundings.

There are in fact two possibilities in connection with the escape
of gas and/or the outflow of liquid:
- there is an immediate outbreak of fire, which may occur if the
gas is combustible and ignition takes place;
- a cloud of gas (gas/air mixture) is formed, which is often com-
bustible and may even be explosive.

2.4.1 Burning contents of tank

It may happen that the contents of the tank catch fire due to any
particular cause. In the event of a serious leakage of gas (e.g.,
through a hole in the roof) it may, for reasons of safety, be con-
sidered advisable deliberately to set fire to the contents. To do
this, it is necessary to make advance arrangements for such a con-
tingency, namely, by providing a source of ignition.

When the tank contents are alight, combustion will take place above
the surface of the liquid in the tank, because there the air is
mixed with the gas formed by evaporation. The liquid therefore burns
at its surface only. A considerable amount of heat is evolved in the
blaze that develops, and the temperature may rise to many hundreds
of degrees Centigrade, depending on the type of gas and on the com-
position of the gas/air mixture.

Now it is of utmost importance to keep this fire localized inside
the tank wall. Hence the wall should be able to withstand this
"fire load", i.e., the wall should in any case remain intact below
the liquid level in the tank. The tank will then burn out like a
"torch", while the level of the liquid will steadily go down (e.g.,
at a rate of 0.3 - 1 m per hour) as it burns.
Fig. 7. Radiation of heat from an LNG fire in a tank of 100,000 m³ capacity and in a catch basin, according to American investigations [6-3].

Distances measured from centre of area under consideration on the lee-side of the tank.

Two wind velocities, 0 km/h and 48 km/h.

Tank within safety wall 62 m dia.:
35 m above ground level (—)

Tank free-standing, with earth bank forming 175m x 175 m catch basin:
5 m above ground level (—)

1. 5450 Btu/hft² danger limit for installations at wind 48 km/h
2. 3300 Btu/hft² danger limit for people at wind 48 km/h
3. 2920 Btu/hft² danger limit for installations at wind 0 km/h
4. 1760 Btu/hft² danger limit for people at wind 0 km/h

(1 Btu/hft² = 3.15 W/m²)
The flames from such a fire may leap to a great height: for burning LNG (liquefied natural gas) a height equal to three times the diameter of the tank is reported [6-16]. In tests performed with LNG at China Lake, however, the height of the flames was much higher - more like six times the tank diameter. During a fire in a tank containing LNG at Cleveland, U.S.A., flames rising to heights of 800 - 900 m were observed. In this case the tank was only 21 m in diameter, but it was a spherical one and had probably exploded [6-17].

A burning tank radiates a considerable amount of heat. For LNG the heat radiation is put at 100 - 150 kW per m² of burning surface area [6-1 and 6-5]. The radiant heat may have serious consequences to the surroundings of a tank on fire (persons, installations, buildings, etc.). By way of example, fig. 7, based on American data, indicates the calculated rate of heat radiation from LNG burning in a storage tank with a height of 62 m and a diameter of 35 m [6-3]. In this diagram the danger limit for human beings is assumed at a radiation rate of 3300 Btu/h.ft² = 10410 W/m². This figure is valid for a wind velocity of 48 km/h = 13.3 m/s. Under windless conditions the rate of cooling is much lower, so that the danger limit is lowered to 1750 Btu/h.ft² = 5520 W/m².

It appears from this diagram that with wind blowing at a velocity of 13.3 m/s there is serious danger of burning to persons within a distance of 460 ft = 140 m from the tank. In the other case (no wind) this distance is 520 ft = 159 m. (The difference between the two distances is not very great because the tank in question is a high one).

In a study conducted in the Netherlands it was basically assumed that a human being is at risk from burning when exposed to heat radiation of about 3000 W/m² [6-1]. With this value, the safe distance as envisaged in fig. 7 would be about 210 m, both for a wind velocity of 48 km/h and under windless conditions.

Obviously, the heat radiation to the surroundings will be less severe if the fire is located at greater height above ground and
also if it is confined to a smaller area. From this point of view it will therefore be preferable to build the storage tank as high as possible and with the smallest possible diameter. The same considerations apply to a safety wall around a tank and to a catch basin formed by a wall or earth bank, because the liquid that may escape from the tank into the gap between it and the safety wall or into the basin may catch fire.

Fig. 7 also gives, by way of example, the calculated heat radiation from burning LNG in a square catch basin measuring 175 m x 175 m and surrounded by a 5 m high wall. On account of the larger area and lower height, the danger limit for human beings in this case is at a greater distance than in that of the storage tank considered above, namely, at 984 ft = 300 m for a wind velocity of 13.3 m/s or 1200 ft = 366 m for windless conditions. (The difference between the two distances is also relatively greater than in the case of the tank, as the latter is narrower as well as higher).

In a study undertaken in the Netherlands a safe distance of 510 m was found for a circular catch basin of 127 m diameter. The difference with regard to the American results is due mainly to the adoption of a lower danger limit in the Dutch calculations.

2.4.2 Escape of gas

If leakage develops above the surface level of the liquid, in the tank wall or roof, escape of gas will occur. This escape will proceed at a faster rate according as the leak or hole is larger, further intensified by the higher rate of evaporation that then occurs. The escape of a small quantity of gas will often not give rise to any special problems, for it will generally be a fairly easy matter to seal a minor leak. According as the storage temperature is further below 0 °C, the more likely is it that ice formation will form a temporary seal, unless overpressure in the tank prevents this.

If a large quantity of gas escapes, a gas/air mixture will be formed outside the tank, which with the majority of gases is combustible
and even explosive in character if the mixture contains a percentage of gas situated between the limits of flammability (see Table 1, page 18). This critical gas/air mixture may be ignited by a source of ignition (electric spark, naked flame, etc.). If this occurs at the tank itself, a fire will break out inside the safety wall or within the wall or bank of the catch basin, the conditions then being similar to that of a tank whose contents are on fire (see 2.4.1).

But if no direct ignition occurs in or near the tank, a cloud of gas will be formed. In that case a situation comparable to an outflow of liquid will arise (see 2.4.3), though of more limited extent. The escaped gas at first has a low or very low temperature (only a few degrees above the boiling point: see Table 1, page 18), depending on the type of gas, and is therefore liable to cause frost injury to persons, while above a certain concentration the gas is likely to cause breathing difficulties. Besides, some gases are toxic.

2.4.3 Outflow of liquid

If leakage develops below the liquid surface level, liquid will flow out of the tank. This will of course occur more rapidly according as the leak or hole is larger and the depth of liquid above it is greater. If only a small quantity leaks out, this need not cause any special problems. The leak can often be temporarily sealed by quite simple means, which may be facilitated by ice formation. In most storage systems, however, even a small quantity of cold liquid will be enough to damage the insulation, so that this too will have to be repaired.

Of course, the consequences are bound to be much more serious when a substantial quantity of liquid flows out of the tank. The cooled liquid will thus come into contact with surfaces that are much or indeed very much warmer, so that the liquid will evaporate to form gas. At first contact with the warmer conditions this evaporation proceeds very rapidly ("initial flash"), but afterwards the rate of evaporation slows down because the supply of heat diminishes.
This is because the warmer surfaces will cool and perhaps freeze up; besides, it may well be that the layer of gas that forms between the cold liquid and the warm surface has an insulating effect.

The gas given off by the evaporating liquid forms a gas/air mixture which may be dangerous (see 2.4.2). If this mixture does not ignite in or near the tank, a cloud of gas will form which may quickly increase in size. Its size will depend, inter alia, on the quantity of gas produced by evaporation, on the nature and size of the evaporation surfaces, and on weather conditions.

Some gases, e.g., the gas given off by LNG, are at first heavier than air, but become lighter as they acquire the ambient temperature. The gas cloud will gradually rise in consequence; this will of course occur more particularly on the lee side of the tank. Other gases, however, remain heavier than air, so that the gas cloud travels almost entirely in a horizontal direction with the wind. This situation arises, for example, with liquefied petroleum gas (LPG) (propane and butane).

If the percentage of gas in the gas/air mixture is close to the upper or the lower limit of flammability, "combustion" will usually occur with a relatively low flame velocity. However, if the gas content of the mixture is lower or higher, respectively, so that the mixture is well within the explosive range, explosive combustion may occur, giving rise to a pressure wave. If flame propagation proceeds at subsonic velocity (e.g., 20 - 60 m/s) and the explosion pressure developed is low, the explosive combustion is known as deflagration, in which the rise in temperature is accomplished by thermal conduction or by heat transfer. On the other hand, if supersonic flame velocity occurs and high explosion pressures develop (of the order of 20 bar), the phenomenon is known as detonation. In that case the rise in temperature is brought about by a shock wave (blast).

The hitherto prevailing view, and indeed one that is gaining wider acceptance, is that in a "free" gas cloud as envisaged here no
detonation can occur [6-1, 6-2 and 6-17]. Theoretically, detonation is possible under such conditions, however, though difficult to achieve in actual fact. The subject is still under research.

The phenomenon of deflagration, though less violent than detonation, may nevertheless have very serious consequences to persons and installations. This is because this form of explosive combustion produces a high temperature and causes considerable heat radiation, accompanied by an explosion pressure build-up (of the order of 0.1 - 0.3 bar).

There is (as yet) no agreement of opinion as to the size that a gas cloud may attain. Hence it is not yet possible to say anything definite about the magnitude of the consequences of a possible explosion. From tests on a limited scale and from a few accidents that have occurred in actual practice it has, however, emerged - as is indeed borne out by theoretical studies - that the consequences of an explosion of a gas cloud can be very serious.

Fig. 8 gives, by way of example, the results of American calculations relating to the formation of a cloud of gas due to the evaporation of LNG in a tank 62 m in diameter and 35 m in height and also in a square catch basin measuring 175 m x 175 m with a 5 m high enclosing wall [6-3]. In this treatment of the problem the safe distance has been put at a gas percentage of 40% of the lower limit of flammability (0.40 LLF; LLF = 5.3% CH₄ = 0.00235 lb of CH₄ per ft³ of air), with the further assumption that it must then still be possible to ignite the gas cloud and thus initiate its explosion.

From the diagram it emerges that for the catch basin the safe distance is no less than 19685 ft = 6000 m, both at ground level and at the level of the centre of the gas cloud. In the case of the tank, however, there is found to be no danger at ground level. Hence the greater height and smaller diameter of the tank wall are favourable in this respect as well. At the level of the centre of the cloud, about 45 m above ground, the safe distance is 689 ft = 210 m.
Fig. 8. Dispersion of gas on evaporation of LNG in a tank of 100,000 m³ capacity with a safety wall (—) and in an open tank (—), under stable weather conditions (class F), wind velocity 2.24 m/sec., according to American investigations \(^6-3\) \(^7\)

Tank within safety wall 62 m dia.:
35 m above ground level (—)

Tank free-standing, with earth bank forming 175 m x 175 m catch basin:
5 m above ground level (—)

1. gas content at ground level
2. gas content at centre of gas cloud

Lower limit of flammability (5.3% = 0.00235 lb CH₄/ft³ air) at ground level, in the event of a disaster affecting in an open catch basin, is at 7300 ft from centre of tank (lee-side).

At 19685 ft there is, at ground level, still 40% of the gas concentration corresponding to the lower limit of flammability, i.e., 0.00096 lb CH₄/ft³ air.

In the event of a disaster affecting a tank within a tank wall, 40% of the quantity of gas corresponding to the lower limit of flammability at the centre of the cloud is found to occur at 800 ft from the centre of the tank.
In investigations conducted in the Netherlands the safe distance was put at 0.50 LLF, i.e., at 50% of the concentration corresponding to the lower limit of flammability [6-1 and 6-2]. According to these investigations, outflow of liquid into a catch basin of 80 - 100 m diameter could cause a gas cloud of 300 - 400 m diameter to form. The 0.50 LLF limit would then be situated at a distance of 500 - 2000 m, depending on weather conditions, etc.

It is not possible to obtain from the available sources of information a definite answer to the question whether, in the event of ignition of a cloud of gas, there occurs "flash-back" of the flame to the source of the cloud.

According to American investigations [2-7 and 6-17], values of between 1 and 75 km have been found for the distance over which a "critical" cloud of gas (LNG) can travel, a result which merely confirms that there is no concurrence of opinion on this point either. The highest values have, incidentally, been calculated for liquid outflow and evaporation at sea.

Since the outflow of liquid is liable to have very serious consequences, even according to the most optimistic estimates and calculations, the structure of a storage tank as a whole should be able to prevent further discharge of liquid in the event of leakage. Structural features such as an outer tank and especially a safety wall should therefore be able to withstand the special loads occurring under such conditions: not only the low temperature ("temperature shock"), but also the liquid pressure which can act as an impact load ("liquid impulse") [6-23].

Unchecked flow of liquid out of a leaking tank can moreover endanger people in the vicinity, mostly presenting an even more serious hazard than the escape of gas (see 2.4.2). The consequences of the unchecked outflow of liquid will be much more serious if a large quantity of cold liquid gushes out in a very short time. This could happen if a tank suddenly failed, whatever the cause of failure might be.
2.5 Review of possible problems

Table 2 summarizes the possible problems, with their undesirable consequences, as described in this chapter.

Table 2. Summary of possible problems

<table>
<thead>
<tr>
<th>Possible problems (see 2.3)</th>
<th>Undesirable consequences (see 2.4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>burning contents of tank</td>
</tr>
<tr>
<td></td>
<td>(see 2.4.1)</td>
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</tbody>
</table>

**internal causes (see 2.3.1)**

- **process engineering causes**
  - gas overpressure (see 2.3.1.1) - x x x
  - gas underpressure (see 2.3.1.2) - x x x
  - overfilling (see 2.3.1.3) - x x x

- **structural causes**
  - mistakes and defects in design, execution and materials (see 2.3.1.4) (including: failure of tank) - x x x

**external causes (see 2.3.2)**

- nearby fire (see 2.3.2.1) x x -
- nearby explosion (see 2.3.2.2) x x x
- fragments hurled away (see 2.3.2.3) x x x
- sabotage (see 2.3.2.4) x x x
- aircraft, etc. (see 2.3.2.5) x x x
- natural phenomena (see 2.3.2.6) x x x
Concrete is an artificially composed conglomerate of coarse and fine mineral particles (usually gravel and sand) which are bonded together with cement as the binding agent. This conglomerate hardens to a stone-like mass. The mineral particles (called aggregates) are mixed with cement and water in the correct proportions. The resulting mixture is called concrete.

Freshly mixed concrete is of plastic consistency and can be cast or moulded into any desired shape. This is done by placing it in moulds or in formwork, after which it is compacted. It then gradually hardens as a result of a chemical reaction between cement and water. After a few weeks the hardened concrete will have attained a considerable proportion of its final strength. However, the process of hardening, i.e., strength development, continues for a long time, though at a diminishing rate.

Concrete can be made wherever the above-mentioned raw materials are available. This offers the great advantage that concrete structures can be made entirely "on the spot", i.e., the constituent materials can be combined and mixed on the site of the job, and the concrete cast in formwork set up for the purpose (in-situ concrete). Alternatively, however, the concrete structural components may be cast in some convenient place away from the site and then, when they have hardened, transported to the site and assembled there (prefabricated construction with precast concrete units).

Concrete possesses a wide range of properties which make it particularly suitable as a construction material. Besides, these properties can be varied greatly in accordance with the rules and possibilities of concrete technology, more particularly, by the choice
of constituent materials, their mix proportions, the compaction applied to the fresh concrete at the time of moulding or casting, and - in the case of concrete structures - the dimensions. Furthermore, certain properties of the freshly mixed and/or the hardened concrete can be modified by the addition of one or more admixtures to the mix.

Present-day concrete technology has a long history behind it, which has yielded a great deal of practical experience, research results, theoretical knowledge, etc.

In the Netherlands (as in most other countries) there are certain standards for the constituent materials (e.g., Netherlands Standard NEN 3550 for cement and NEN 3542 for sand and gravel). The design and construction of concrete structures have to comply with certain sets of rules (codes of practice); in the Netherlands these are more particularly contained in the Voorschriften Beton VB 1974 (NEN 3861 to 3867) [1-4 to 1-10]. These codes also comprise quality control.

In common with other stone-like materials, concrete is better able to resist compressive stresses than tensile stresses. The compressive strength is usually in the range of 30 - 50 N/mm², but may be considerably higher if special mix compositions and concrete-making techniques are employed. The resistance to tensile loads, i.e., the tensile strength, of concrete is only about one-tenth of the compressive strength.

The relatively low tensile strength is no disadvantage so long as concrete is not, or hardly, loaded in tension. In circumstances where tensile stresses of significant magnitude will occur, arrangements to resist these stresses have to be made. In principle, there

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*Some Dutch codes are mentioned in this report. Similar requirements, as in these codes, can be found in other national standards, codes of practice or recommendations. It is impossible to mention all of them in this report.*
are two different techniques for doing this. The older technique, which emerged in the latter part of the previous century, consists in "reinforcing" the concrete, the material then being known as reinforced concrete (see 3.3). The other technique, of more recent origin, but now almost half a century old, consists in "prestressing" the concrete, which is then called prestressed concrete (see 3.4).

As an alternative or an adjunct to conventional reinforcement with steel bars, a quantity of "fibres" (usually of steel) can be incorporated in concrete. Such fibre-reinforced concrete (see 3.5) possesses some special properties; besides, it can be reinforced in the usual way or prestressed.

3.1.2 Properties

Concrete as a construction material possesses a wide range of properties. For structures intended for "unpressurized cooled storage" (as envisaged in this report) certain properties are of special importance and will therefore be described in further detail below. What is more particularly of interest is the behaviour at low temperatures, the liquid- and gas-tightness, the behaviour at high temperatures, and the behaviour in the event of a rapid change in temperature.

3.1.2.1 Low temperatures

Concrete is used also in regions with extremely low air temperatures (down to around -50 °C), as in Canada, the United States and the USSR. Even under such severe conditions of service concrete has proved satisfactory in practice.

In order to improve the frost resistance of the hardened concrete, a special admixture (usually a so-called air-entraining agent) may be added to the concrete in the mixer, with the result that a large number of tiny air bubbles (about 0.2 mm diameter) are incorporated in the concrete. This method of improving the low-temperature behav-
1 stored under water
2 stored at 50% relative humidity
3 dried at 105°C

Fig. 9. Compressive strength and splitting tensile strength of concrete stored at various values of humidity during hardening, at temperatures down to -157 °C [3-2]
our is, generally speaking, necessary only if the concrete is to be subjected to a large number of repetitions of freezing and thawing.

In connection with "unpressurized cooled storage", investigations on the effect of low temperatures (down to -196 °C = boiling point of nitrogen) on the strength of concrete have been carried out in America and elsewhere.

The compressive strength of concrete at these low temperatures is found to be at least equal to that at normal temperatures and under certain circumstances even to increase. The increase in compressive strength (sometimes by as much as 200 - 300%!) is greater according as the concrete contains more water (fig. 9). It is due to the freezing of water in the pores of the concrete.

The splitting tensile strength, like the compressive strength, remains at least unchanged, or even increases somewhat, at low temperatures. The relation between compressive strength and splitting tensile strength existing at normal temperatures (around 20 °C) is likewise preserved under low-temperature conditions (fig. 9).

The modulus of elasticity of concrete, which characterizes its rigidity, shows an increase at low temperatures, provided that the concrete contains water. This increase is, under equal circumstances, relatively smaller than the increase that occurs in the compressive strength and splitting tensile strength. So far, little information is available concerning the effect of temperature variations on the magnitude of the modulus of elasticity. It is therefore advisable to adopt a cautious approach in using concrete for those structural parts which are in contact with air containing water vapour and which are moreover subjected to large variations in temperature (cooling - heating). The concrete to be used should first be duly tested under service conditions in order to ascertain how its properties are affected by those conditions [3-28].

The coefficient of thermal expansion of concrete is given as 12 x 10^-6 per °C at normal temperatures (about 20 °C) in the
Netherlands Code VB 1974 (NEN 3861) [1-4]. At low temperatures, however, it decreases to $7 - 8 \times 10^{-6}$ per °C on an average.

**Note:** VB 1974 gives a value of $12 \times 10^{-6}$ per °C for the coefficient of thermal expansion at normal temperatures both for reinforcing steel and for prestressing steel in reinforced concrete and in prestressed concrete. At low temperatures this coefficient is found to decrease less for steel than it does for concrete (see 3.2.2). This means that, on cooling, steel undergoes a greater amount of shortening than concrete does, with the result that, in a structure in which the steel and concrete are fully connected to each other by bond, the steel will be placed under tension and the concrete under compression. This is taken into account in the structural design calculations.

3.1.2.2 **Liquid-tightness**

Concrete has long been used for the construction of water-retaining structures and for containers and channels for the storage and transport of water. For such purposes, concrete is regarded as "watertight", this view being of course borne out by experience gained in practice. However, since concrete is actually a "porous" material, a certain amount of water penetration to a limited depth into it will always occur. This penetration can be reduced by the addition of "water-proofing agents" to the concrete at the time of mixing (these are special admixtures or very finely divided aggregates).

Concrete has also for some considerable time been used for the storage of liquids other than water, such as oils and other combustible liquids [1-16 and 7-15 to 7-17]. The penetration of such liquids into the concrete depends on their density, viscosity, storage temperature and storage pressure.

For the storage of low-viscosity liquids it may be necessary to provide the concrete with a liquid-excluding layer, i.e., a covering which is impermeable to the liquid to be stored in the concrete.
vessel. Such layers comprise coatings, membranes and liners. They may often also serve to protect the concrete from the action of liquids which are chemically aggressive to it.

Such arrangements may also be necessary for "unpressurized cooled storage" in concrete vessels. The low storage temperature will, however, often have a favourable effect in that it may improve the liquid-tightness, i.e., the impermeability, of the concrete. These arrangements may, if necessary, also serve to ensure the desired vapour-tightness of a concrete structure (see 3.1.2.3).

3.1.2.3 Vapour-tightness

Although concrete is "water-tight" (see 3.1.2.2), it is permeable to water vapour. The amount of vapour that passes through the concrete will depend upon, among other factors, the differences in vapour pressure and relative humidity between the concrete and its environment, as well as on the dimensions of the concrete structure.

The permeability to vapour will be greater according as the concrete is drier. Although the amount of vapour that makes its way through the concrete is relatively small even under unfavourable conditions, it may, for "unpressurized cooled storage", be necessary to prevent the penetration of water vapour into the tank. It is more particularly important to exclude water vapour from the cavity containing the insulating material, because moisture impairs the insulating

\[\text{In this report these terms have the following meanings:}\]

- a coating is a fairly thin layer, often of plastic, which is applied in a liquid or semi-liquid condition to the hardened concrete surface;
- a membrane, often of metal or plastic, is a thin layer which possesses practically no intrinsic rigidity and can therefore be deformed almost stress-free;
- a liner, consisting of metal (often steel) or possibly some other material, is usually at least 3 mm thick, so that stresses develop in it on deformation.
effect thereof. There is generally a low temperature in the insulation cavity, so that a relatively large difference in vapour pressure between the inside and the outside of the concrete wall will develop. In that case the rate of vapour transport through the concrete will not be negligible. In order to prevent the ingress of water vapour, arrangements similar to those for improving the liquid-tightness of the concrete may be employed, i.e., coatings, membranes or liners (see 3.1.2.2 and 6.5).

With "unpressurized cooled storage", vaporized liquid (i.e., gas) may penetrate and pass through the concrete in the same way as water vapour does. Under such conditions the liquid "evaporates" through the concrete, as it were. The rate at which the gas will thus make its way through the concrete will depend of course on the difference in vapour pressure on the inside and the outside of the tank wall.

The gas formed by evaporation will, in the cases envisaged here, generally have a low temperature - only a few degrees above the boiling point of the liquid concerned. This low temperature will have a favourable effect on the vapour-tightness of the concrete, for the permeability is reduced by thermal contraction due to cooling and, if the concrete is moist, by freezing of the water in the pores. This favourable effect will gradually disappear as the gas warms up. Yet the rate of gas transport through the concrete (i.e., the amount that passes through it per unit time) will not greatly increase as a result of this, one probable reason being that the viscosity of the gas increases with higher temperature.

Although concrete is certainly not absolutely gas-tight, calculations show the rate at which gas passes through it to be of limited magnitude. The data that are available for such calculations ~3-7, 3-12, 3-14 and 3-15~ show a fairly considerable amount of scatter, which is understandable, since they relate to different conditions.

If complete vapour-tightness is desired for concrete structures intended for "unpressurized cooled storage", and also if the amounts
of gas passing through the walls are considered too large, it will be necessary to apply vapour barriers, i.e., vapour-tight layers (coatings, membranes or liners: see 3.1.2.2).

3.1.2.4 High temperatures

As is generally known, concrete has a high resistance to fire. It is "incombustible" and effectively resistant to temperatures up to about 600 °C. Particularly in connection with the desired "fire resistance" of structures, numerous investigations for ascertaining the effect of high temperatures on the properties of concrete have been carried out over the years.

The compressive strength of concrete is found to undergo little or no change at temperatures up to 250 - 300 °C. If the concrete contains water, there even appears to be an increase in strength at elevated temperatures (fig. 10). This strength increase is assumed to be due to the continuation of the chemical reaction (hydration) under the influence of the heat supplied. If the temperature rises above about 250 - 300 °C, the strength of the concrete gradually declines (fig. 10).

At temperatures above 500 - 550 °C a process of disintegration of the concrete sets in, resulting in a considerable decrease in strength. Since concrete possesses a tremendous "buffering capacity" (see 3.8), it takes a relatively long time to heat up. Because of this, the temperature at which disintegration occurs will not penetrate to the core of the concrete wall or other member until a fairly long time has elapsed.

If concrete is exposed to much higher temperatures than about 600 °C, disintegration will certainly occur. However, if the concrete is provided with reinforcing steel (reinforced concrete), it will continue to form a more or less coherent whole for some considerable length of time even at such high temperatures.
Concrete in structures will usually be loaded in compression, e.g., under the action of prestress. Research has shown that the decrease in strength at high temperatures in that case is often less pronounced than it would be in the absence of such compressive loading.

The splitting tensile strength of concrete at high temperatures behaves in much the same way as the compressive strength.

The modulus of elasticity of concrete decreases at high temperatures, just as the compressive strength does.

The coefficient of thermal expansion increases at high temperatures, the rate of increase being about $3 \times 10^{-6}$ per 100 $^\circ$C of rise in temperature. This effect, however, is found to be less pronounced if the concrete is loaded in compression (as in prestressed concrete).
3.1.2.5 Temperature changes

Just as in many other materials, changes in temperature in concrete cause deformations: a rise in temperature causes expansion, a fall in temperature causes contraction of the concrete. Temperature changes may occur slowly or very slowly, e.g., in consequence of the difference in air temperature between day and night or between summer and winter. The deformations, and the associated stresses, caused by these changes can be effectively resisted by concrete structures, provided that they are correctly designed and detailed.

Structures for "unpressurized cooled storage" may, however, be subjected to temperature changes which take place within a very short time, especially at the surfaces of such structures. Thus, a rapid fall in temperature may occur if the tank is filled too quickly with cold liquid and will certainly occur if a large quantity of cold liquid flows out of the tank and encounters a much warmer structural component. (On first contact, the cold liquid will at once evaporate vigorously; the thin layer of gas which forms between the liquid and the structural component in consequence of this evaporation could act as an insulating barrier) (see 3.8.3). A rapid rise in temperature can be expected if there is an outbreak of fire in the vicinity of the storage structure. If the contents of the tank catch fire, the temperature at the surface of the tank wall will rise very quickly, but the average temperature of the wall will rise only at a gradual rate. However, the non-uniform temperature distribution through the thickness of the wall will then play a part.

From the data now available it emerges that concrete, and structures built of this material, are fairly well able to withstand such "temperature changes". An important factor in this connection is the high "buffering capacity" of concrete (see 3.8), as a result of which the temperature changes only penetrate slowly into the concrete structures. Also of importance is the presence of reinforcement and of prestress in the concrete (see 3.8), having regard to the fact that the non-uniform temperature distribution through the concrete cross-section is liable to cause large tensile stresses in it.
3.2 Reinforcing steel, prestressing steel, anchorages

3.2.1 General

On account of the relatively low tensile strength of concrete, structures built of this material and subjected to tensile loads are "reinforced" (see 3.3) or "prestressed" (see 3.4), so that these loads are resisted by reinforcement and/or prestress.

"Reinforced concrete" is provided with reinforcement consisting of steel reinforcing bars. These bars are suitably assembled and fixed in position beforehand, and the freshly mixed concrete is then placed around them.

In "prestressed concrete" a compressive stress ("prestress") is produced beforehand in the concrete, usually with the aid of steel with a high tensile strength: prestressing steel, in the form of wires, bars or strands. These may be used as individual units or may be grouped into larger units ("cables"), the general term "tendon" being used to denote a single or composite functional unit of prestressing steel.

The prestressing steel may be installed in ducts preformed in the concrete. The steel is then "tensioned", i.e., stretched to produce a tensile stress of a certain magnitude in it, and the ends of the tendons are secured by means of special anchorages so as to maintain the steel under tension. Finally, the ducts are "grouted", i.e., injected with a cement paste or mortar. This procedure is known by the general designation of "post-tensioning", the structure being described as made of "prestressed concrete with post-tensioned tendons".

For cylindrical structures, such as storage tanks and safety walls, the prestressing steel may alternatively be applied by the so-called wrapping or winding method. In that case the steel wire tendon is wrapped in a continuous spiral around the outside of the wall and is tensioned at the same time. Finally, the whole steel-wrapped
wall is given a protective covering of "gunite" (pneumatically sprayed concrete). In this technique there are no special anchorages such as those used in post-tensioning.

Another method consists in tensioning the prestressing steel between fixed strong supports to which it is temporarily anchored. Concrete is then cast around the steel and, after the concrete has hardened, the anchorages are released. The embedded steel is now held permanently under tension, being gripped by bond in the concrete, and thus produces the required prestress in the latter. This technique, which is used more particularly for the production of prestressed precast concrete and is applied chiefly in concrete precasting works, is called "pre-tensioning".

3.2.2 Reinforcing steel

The reinforcing steel used in reinforced concrete consists of an alloy of iron with various other chemical elements, including more particularly carbon. The carbon content is always rather low, however.

In Netherlands Standard NEN 6008 [1-3] three grades of steel are distinguished: a mild steel (FeB 220) and two higher-grade ("high-tensile") steels (FeB 400 and FeB 500). The higher grades are produced by increasing the carbon content to about 0.3 - 0.4% (as against 0.1 - 0.2% in mild steel). Alternatively, however, the increase in strength can be obtained by means of subsequent treatment (e.g., cold working).

NEN 6008 states the requirements that reinforcing steel must fulfil at room temperature (about 20 °C) in order to be suitable for use in reinforced concrete construction (see note on page 50). Table 3 indicates some of the required mechanical properties. As appears from the table, there are no specified requirements for the notch sensitivity of this steel.
Table 3. Some requirements applicable to reinforcing steel at approx. 20 °C [1-3]

<table>
<thead>
<tr>
<th></th>
<th>FeB 220</th>
<th>FeB 400</th>
<th>FeB 500</th>
</tr>
</thead>
<tbody>
<tr>
<td>characteristic yield point or 0.2% proof stress</td>
<td>220 N/mm²</td>
<td>400 N/mm²</td>
<td>500 N/mm²</td>
</tr>
<tr>
<td>characteristic tensile strength</td>
<td>340 N/mm²</td>
<td>500 N/mm²</td>
<td>550 N/mm²</td>
</tr>
<tr>
<td>elongation at fracture (A5)</td>
<td>24%</td>
<td>14%</td>
<td>12%</td>
</tr>
<tr>
<td>elongation before reduction of area (min.)</td>
<td>2,5%</td>
<td>2,5%</td>
<td>2,5%</td>
</tr>
</tbody>
</table>

From various researches it has emerged that low temperatures may have an unfavourable effect on the mechanical properties of reinforcing steel. On cooling, the toughness undergoes a considerable reduction. Besides, the notch sensitivity increases, with the attendant risk of brittle fracture of the steel at low temperatures. For these reasons, reinforcing steel will, unless it has been investigated in more detail, have to be regarded as not suitable for structures destined for "unpressurized cooled storage" which are exposed to (very) low temperatures. The use of the steel is therefore permissible only if its properties at the relevant storage temperature are sufficiently known. Besides, there are types of reinforcing steel available which retain their favourable properties even under these extreme conditions. For storage temperatures above about -20 °C, however, reinforcing steel may be used without further investigation.

The adverse effect of low temperatures upon the properties of reinforcing steel are attributable to the composition and quality of the steel. In view of the possibilities of application, relatively low demands are made upon the strength of reinforcing steel, and for this reason a relatively large range of scatter in the strength values is allowed.
Some grades of reinforcing steel, of special composition and quality, are immune to the unfavourable effect of low temperatures. Such steel is therefore more particularly suitable for the reinforcement of concrete structures intended for "unpressurized cooled storage". In contrast with most types of reinforcing steel, prestressing steel generally behaves favourably at low temperatures (see 3.2.3). This steel is therefore also suitable for use as (conventional) reinforcement in concrete structures exposed to low temperatures, i.e., it is not tensioned when used in this way.

3.2.3 Prestressing steel

Like reinforcing steel, the prestressing steel to be used in prestressed concrete construction consists of an alloy iron and other elements, especially carbon. The carbon content is higher, however, about 0.6 - 0.8%. By virtue of its composition and/or subsequent treatment in the manufacturing operations this steel possesses a high tensile strength. Its mechanical properties may be further improved by appropriate thermo-mechanical processes [1-23].

Netherlands Standard NEN 3868 [1-11] and Euronorm 138 [1-22] state the requirements that prestressing steel must fulfil at room temperature (about 20 °C) in order to be suitable for use in prestressed concrete construction. Three grades of steel are distinguished in this Standard: FeP 1670, FeP 1770 and FeP 1860 (see note on page 50). Table 4 indicates some of the required mechanical properties. As appears from the table, there are no specified requirements for the notch sensitivity of this steel.

Table 4. Some requirements applicable to prestressing steel at approx. 20 °C [1-11]

<table>
<thead>
<tr>
<th></th>
<th>FeP 1670</th>
<th>FeP 1770</th>
<th>FeP 1860</th>
</tr>
</thead>
<tbody>
<tr>
<td>characteristic tensile</td>
<td>1670 N/mm²</td>
<td>1770 N/mm²</td>
<td>1860 N/mm²</td>
</tr>
<tr>
<td>strength (standard</td>
<td>(40 N/mm²)</td>
<td>(40 N/mm²)</td>
<td>(40 N/mm²)</td>
</tr>
<tr>
<td>deviation)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>characteristic 0.1%</td>
<td>1420 N/mm²</td>
<td>1520 N/mm²</td>
<td>1620 N/mm²</td>
</tr>
<tr>
<td>proof stress (standard</td>
<td>(50 N/mm²)</td>
<td>(50 N/mm²)</td>
<td>(50 N/mm²)</td>
</tr>
<tr>
<td>deviation)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>elongation at maximum</td>
<td>min. 3.5%</td>
<td>min. 3.5%</td>
<td>min. 3.5%</td>
</tr>
<tr>
<td>load</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The requirements which the Standards lay down for prestressing steel and for reinforcing steel are based on considerations of concrete technology, construction and design. The requirements relating to concrete technology are concerned mainly with durability (rusting, stress corrosion sensitivity, fatigue strength). Constructional requirements relate, inter alia, to the workability of the steel (stress-strain diagram, suitability for wrapping or winding). Design requirements relate, inter alia, to the behaviour of the steel on being subjected to overloading in the structure (uniform strain, stress-strain diagram) and under working load conditions (relaxation behaviour).

No requirements as to the sensitivity to damage, e.g., for notch toughness (notched bar impact test values), are laid down. For the steel used in special prestressing systems such requirements are sometimes applicable, however, occasionally bending tests are performed on wires, provided with a notch, as an additional test for the ductility of prestressing steel.

For building good prestressed concrete structures the quality of workmanship in the execution of the job is an important condition. For this reason the relevant codes (more particularly NEN 3868 1-11 and FIP "Guide to good practice" 1-25) lay down exacting requirements as to workmanship (see note on page 50).

At the time of tensioning, the prestressing steel is subjected to a high stress - higher than any stress it will subsequently attain throughout its service life in the structure. If the prestressing steel is properly installed and tensioned, and if the ducts have been carefully grouted, this steel will under no circumstances be subjected to conditions that necessitate imposing any requirements as to notch sensitivity. In the first place, the prestressing steel or the reinforcing steel is connected and bonded over its entire length to the concrete in which it is embedded (either directly or with the interposition of the subsequently injected grout). Hence the concrete completely protects the steel against any possible mechanical damage. Because of the bond, i.e., the adhesion of
the steel to the concrete surrounding it, the (extra) forces or stresses in the steel are transmitted gradually to it from the concrete, and vice versa. Possible additional deformations of the steel due to cross-sectional changes are limited by the surrounding concrete. Hence heavily ribbed reinforcing bars can permissibly be installed in concrete structures.

Secondly, in the event of overloading of the structure - by impact or other types of load - the steel will, both in uncracked concrete and at possible cracks in reinforced concrete, be subjected only to axial tensile forces. These forces will of course be larger at the cracks (in reinforced concrete) than in uncracked concrete. In connection with this, requirements are laid down with regard to the bond of the steel to the concrete, so as to ensure that the transmission of force between the two materials takes place in a gradual manner. Stress concentrations therefore do not arise.

In this context it is to be noted that the effect of mechanical damage on the tensile strength of prestressing steel and reinforcing steel is very slight. In order to ensure that the anchorages of prestressing tendons are so designed as not to impair the strength of the prestressing steel in the anchorage zone, special requirements are applicable to these devices as well (see 3.2.4).

The requirements laid down for prestressing steel in the standards do not apply to steel used under cryogenic conditions. In so far as this may be necessary, supplementary requirements will have to be specified for such cases. In this report it is merely indicated what qualities the standardized prestressing steel possesses even under extreme low-temperature conditions.

The strength requirements stated in NEN 3868, and therefore in Table 4, relate only to "cold-drawn prestressing wire" and the seven-wire strands made from it. Wires are produced in thicknesses up to about 7 mm, and strands are available with external diameters ranging up to about 12 mm (seven 4 mm wires) and about 15 mm (seven 5 mm wires).
Prestressing bars and "hot-rolled prestressing wire" are not included in NEN 3868, as they are manufactured only by a very limited number of factories and are moreover used only in certain prestressing systems. The tensile strength of thick prestressing bars ranges between about 1030 N/mm² (36 mm diameter) and about 1230 N/mm² (14 mm diameter).

On comparing Table 4 (prestressing steel) with Table 3 (reinforcing steel) it is evident that prestressing steel is much stronger than reinforcing steel. The strength requirements for prestressing steel are indicated in so-called characteristic values based on the statistical analysis of large series of test results. The standard deviation associated with these results is relatively small, so that the relevant requirement was justifiably limited to a maximum of about 2.5% for the tensile strength and of about 3.5% for the 0.1% proof stress. For these reasons the differences in quality of consignments of prestressing steel of the same kind, but supplied by different manufacturers, are much smaller than those commonly found in reinforcing steel.

For prestressing steel to be used in the Netherlands the requirement that it should be supplied under a KOMO certificate is frequently specified. Steel covered by such a certificate is subjected to a careful routine of internal quality control by the manufacturer, while the KOMO organization which issues the certificate closely monitors the manufacturer's compliance with these conditions. The procedure is based on NEN 3868. The supervisory function performed by, or on behalf of, KOMO extends to the manner of manufacturing the steel and to the manner in which the manufacturer carries out his contractually agreed scheme of internal quality control. In addition, an external (independent) analysis of the test results derived from the internal quality control is periodically carried out. For that purpose the results are subjected to a verification procedure both with regard to the material and to the personnel concerned. This procedure aims at the detection and elimination of any systematic errors that may have crept into the internal quality control routine. The use of uncertified prestressing steel
should, strictly speaking, not be allowed other than in exceptional cases. See, in this respect also FIP-report 5/6 [1-24] and the note on page 50.

In connection with "unpressurized cooled storage", investigations have been carried out with a view to ascertaining the effect of low temperatures (down to -196 °C) on the properties of prestressing steel. For the commonly employed types it appears that the tensile strength (fig. 11) and the 0.1% proof stress never decrease, but always increase, at low temperatures. The ratio between these two strength properties is found to remain practically constant (fig. 12).

![Graph showing the effect of temperature on the tensile strength of different steels.](image)

Fig. 11. Effect of temperature on the tensile strength of the following steels:
1 = 5.08 mm drawn and stabilized
2 = 7 mm drawn and stabilized
3 = 5 mm drawn and heat-treated
4 = 5 mm drawn and stabilized
5 = quenched and tempered (in the form of bars)
6 = McAlloy bars
Fig. 12. The influence of temperature on four properties of pre-stressing steel (Shinko wire)

At low temperatures the modulus of elasticity displays approximately the same behaviour pattern as the tensile strength and 0.1% proof stress.

The coefficient of thermal expansion decreases at low temperatures, though to a less extent than that of concrete (see 3.1.2.1). In the event of a fall in temperature the steel in prestressed concrete will therefore tend to shorten more than the concrete will. As a result, the tensile stress in the steel will increase, so that the compressive stress in the concrete (the "prestress") likewise increases, which is often a favourable development (see 3.4 and 3.8).
For the most commonly used prestressing steels the elongation at fracture (ultimate strain) undergoes some decrease with progressively lower temperature, but only at a gradual rate, so that the steel retains a fair degree of ductility even at -196 °C (fig. 12). This is also apparent from the magnitude of the elongation before reduction of area and of the reduction of area (necking or constriction) itself at these low temperatures.

![Graph showing the effect of temperature on impact strength of heat-treated steel.](image)

**Fig. 13. Effect of temperature on impact strength of heat-treated steel [4-2 and 4-7]**

- 1 = without notch
- 2 = V-notch (after attainment of 78% tensile strength)
- 3 = V-notch (after attainment of 90% tensile strength)
- 4 = U-notch

With lowering of temperature the sensitivity to surface damage of the steel shows some increase. By way of example, fig. 13 gives the
results of Japanese tests [4-2 and 4-7], which call for the following comment. In general, prestressing steel is sensitive to the effects of damage. This does not apply so much to the tensile strength. In fact, only the impact strength undergoes a marked decrease. From fig. 13 it is apparent, however, that the effect of temperature on impact strength is more pronounced in the undamaged wires than in the damaged and preloaded wires.

To lay down supplementary requirements for the notch sensitivity of prestressing steel used under cryogenic conditions is not an obvious thing to do. The reasons already stated earlier are valid in this case as well. Besides, a combination of low temperature and axial impact loading in prestressing steel is almost inconceivable. This does not alter the fact that the axial impact strength under the effect of low temperature does deserve attention. As yet, however, no testing method for reliably determining this behaviour has been developed.

Investigations on the effect of high temperatures on the properties of prestressing steel have been carried out more particularly in connection with the desired "fire resistance" of structures (fig. 12). At temperatures up to about 200 °C these properties undergo hardly any change. Above about 200 °C, however, they are adversely affected. For most of the commonly employed types of prestressing steel it can be stated that at about 450 °C (which is the "critical steel temperature") failure occurs at a tensile stress of around 65% of the tensile strength.

In prestressed concrete structures the steel is embedded in concrete, which possesses considerable thermal "buffering capacity" (see 3.8). It therefore takes a fairly long time for heat applied to the outside of such structures to raise the temperature of the prestressing steel to the critical temperature. The "concrete cover" (thickness of overlying concrete) to the prestressing steel can be so chosen that the structure will retain its stability throughout the duration of a fire in the vicinity. Of course, the depth of cover is more particularly important with regard to attaining this fire resistance.
In principle, the same possibilities are available for protecting the steel in the concrete structure against (too) low temperatures. However, in view of the behaviour of the usual types of prestressing steel at such temperatures, these protective measures will often be unnecessary.

It can be presumed that prestressing steel possesses favourable properties even at extreme temperatures. All the same, these properties should always be thoroughly verified before the steel is used in concrete structures for "unpressurized cooled storage".

3.2.4 Anchorages

For prestressed concrete with post-tensioned tendons (see 3.4) a number of systems have been developed, each with its own type of anchorage for securing the tendons in "end blocks", i.e., suitably designed end portions of beams (for example), which ensure that the tensile force in the prestressing steel is effectively transferred to the concrete, which is thus placed under compressive stress (the "prestress").

NEN 3869 and FIP "Guide to good practice" - Appendix state the requirements to be fulfilled by anchorages suitable for use in prestressed concrete construction (see note on page 50). On the basis of this Standard, KOMO certificates are issued in respect of prestressing systems. A certificate of this kind comprises a specification of rules for the correct application of the system and its anchorage, and contains a statement as to its practical effectiveness. No pronouncement on the functioning of the anchorage at extreme temperatures is made in the certificate, however. Research has shown that the types of anchorage most commonly used do in fact continue to function satisfactorily even at extremely high and low temperatures.

3.3 Reinforced concrete

Reinforced concrete is concrete (see 3.1) which contains reinforcement consisting of steel bars (reinforcing steel, see 3.2.2). It is a
combination of two materials: concrete with a high compressive strength and steel with a high tensile strength. As a result of the bond between steel and concrete these two materials are completely interconnected. The steel in reinforced concrete will resist (high) tensile stresses only when the concrete has cracked in consequence of (too) high tensile stresses. So long as there are no cracks, the stresses in the steel will remain small: the steel plays merely a "passive" part. But as soon as the concrete has cracked in tension, the tensile forces acting at the cracks in the concrete will be transmitted by the steel (fig. 14).

Fig. 14. The principle of reinforced concrete: at a crack in the concrete the tensile stresses are resisted by the steel alone.
The cracks in reinforced concrete are an inherent feature of the behaviour of this material. By means of suitable design measures the width of these cracks can be limited to acceptable values, e.g., 0.2 mm or 0.5 mm. The crack width that is considered acceptable or permissible will depend, inter alia, on the conditions of service of the reinforced concrete (humid surroundings, indoor environment, etc.).

The "hair cracks" will, despite their limited width, diminish the impermeability of the concrete to vapour. Its liquid-tightness may also be adversely affected. This is one of the reasons why reinforced concrete is often not very suitable for liquid-retaining structures (see 3.9).

Reinforcing steel in reinforced concrete structures is subjected to almost exclusively axial tensile or compressive loading. It is protected by the concrete against mechanical damage.

3.4 **Prestressed concrete**

Prestressed concrete is concrete (see 3.1) in which, by artificial means, a compressive stress is produced before the actual working load is applied to it. By means of this "prestress" the tensile strength of the concrete is, as it were, considerably increased. Thus the concrete can resist fairly large tensile forces without cracking, as the applied compressive stress first has to be neutralized by the tensile forces before the concrete is actually loaded in tension.

In practice the prestress is often designed to such magnitude that, under normal loads, no tensile stresses will develop anywhere in the concrete (fig. 15). As contrasted with the reinforcing steel in reinforced concrete, the prestressing steel in prestressed concrete does play an "active" part from the outset. (In reinforced concrete the steel is "passive" in the sense that tensile stress develops in it only as a result of the external loading applied to the structure. In prestressed concrete the steel is "active"
Fig. 15. The principle of prestressed concrete:
(a) a compressive stress is produced in the concrete before the actual (external) loading is applied;
(b) the tensile stress produced by the loading reduces the artificially produced compressive stress, but the concrete still remains under compression
because it is under considerable tensile stress already before any external loading is applied to the structure; the steel stress merely undergoes some relatively minor increase in consequence of such loading).

The prestress is generally produced by means of prestressing steel, i.e., steel of high tensile strength, used in the form of wires, bars or strands.

These may be used as individual units or, in the case of wires or strands, be grouped into larger assemblies, conventionally called "cables". The term "tendon" denotes a functional unit of prestressing steel, either a single wire, bar or strand or alternatively a "cable" consisting of a number of wires or strands.

The tendons may be installed in ducts preformed in the concrete. This technique is called "post-tensioning".

In the so-called wrapping or winding method of prestressing, the steel is not installed in the concrete, but wound round it, a technique which is especially suitable for cylindrical concrete structures such as tanks. These tendons wrapped under tension are secured to the structure and are then covered with concrete, usually in the form of sprayed concrete ("gunite").

Particularly for precast concrete units a different prestressing technique is widely employed: "pre-tensioning", in which the tendons are first tensioned between fixed points, after which the concrete is cast directly around them.

Prestressing steel in prestressed concrete structures is only loaded axially in tension. The concrete completely protects it from mechanical damage.

3.5 Fibre-reinforced concrete

A quantity of fibres may be added to the fresh concrete at the time of mixing (see 3.1). These are usually of steel, but other materials
may also be suitable. With steel fibres the resulting concrete is
called "steel fibre concrete", which can additionally be reinforced
or prestressed in the usual way. The steel fibres are usually
0.25 - 0.50 mm in diameter and have lengths ranging from 40 to
150 times the diameter.

Steel fibre concrete has some notable properties, so that it is of
interest also as a construction material for "unpressurized cooled
storage". The added fibres greatly increase the toughness and defor­
mation capacity of the concrete, especially under dynamic loads.
Besides, steel fibres can play an important part in resisting the
effects of imposed (temperature) deformations, because the fibres
can prevent the occurrence of extreme cracking in the concrete.

3.6 Impact loads, hits, etc.

Concrete has already for many years been extensively used as a con­
struction material for military structures such as bunkers, shelters,
etc. In this role it has shown itself to possess fairly high resist­
ance to impact loads, hits from projectiles, etc. Obviously, this
resistance increases with the dimension of the concrete in the
direction of the dynamic loading. For this reason, too, concrete
has come into use for the construction of safety walls, etc. for
nuclear power plants [3-18 and 7-15] in order to protect these
plants from external influences. Structures for "unpressurized
cooled storage" may likewise be subjected to impact loads, hits,
etc. (see 2.3.2.3 to 2.3.2.5).

In connection with the uses of concrete for military purposes, for
nuclear power plants and for "unpressurized cooled storage" various
investigations have been carried out with a view to finding out the
behaviour of concrete structures under the action of impact loads,
hits, etc. Those investigations have been concerned more particu­
larly with the thickness of concrete needed for preventing the
penetration of a bullet, shell or other object (such as flying
fragment from an adjacent explosion).
According to American research (3-25), about 0.17 m of reinforced concrete is sufficient to prevent the penetration of a shell (62.5 mm diameter, 2.3 kg weight, fired at a velocity of 300 m/s). For another type of shell (150 mm diameter, 34 kg weight, fired at a velocity of 240 m/s) this value is over 0.38 m. Concrete structures for "unpressurized cooled storage" have walls at least about 0.45 - 0.50 m thick, so that these structures can stop the above-mentioned shells from penetrating. So-called hollow charges (bazooka, LAW, etc.), however, penetrate much deeper than bullets, shells and other objects with the same or larger diameter. The effect of hollow charges, which is based on a melting action, could be curbed by precautionary arrangements ensuring that the charge explodes before hitting the actual structure.

Some years ago two double-walled prestressed concrete tanks for the storage of LNG, each of 143000 m³ capacity, were built on Staten Island (New York) for the Distigas Corporation. In view of the proximity of three important airports, these tanks were designed to withstand the impact of a Boeing 707 (6-13) and even of a Boeing 747 (8-6), especially the engines (the "hardware") of these aircraft. For this reason a 3 m thick "barrier" of plain (unreinforced) concrete was installed between the inner and the outer tank, both of prestressed concrete. (A similar precaution had been adopted a year previously in the case of two LNG tanks, each of 92500 m³, for the Philadelphia Gas Works at Philadelphia). Calculations have shown that the impact load considered in designing these structures can indeed cause local damage, but will not have disastrous consequences. It is to be feared, however, that little will remain intact of the rest of the installation in the event of such a calamity. The consequences are not to be estimated.

The FIP Commission "Concrete pressure and storage vessels" recently published a formula (1-16) for determining the wall thickness necessary for preventing the penetration of a "projectile" (vertical hit). This formula, originating from the Swiss National Institute of Technology (EMPA), Zürich, relates to reinforced concrete. The
above-mentioned FIP Commission has, however, also used the formula for prestressed concrete, though this material generally possesses even higher penetration resistance.

The formula in question is as follows (adopting the original units):

$$d = \frac{1.5}{\sqrt{f'_c}} \cdot \frac{G}{D^{1.8}} \cdot \frac{4}{V^3} \text{ (for } 150 \text{ m/s} \leq V \leq 300 \text{ m/s)}$$

where:

- $d$ = minimum wall thickness (in cm)
- $f'_c$ = cube strength of the concrete (in kgf/cm$^2$)
- $G$ = weight of the "projectile" (in kg)
- $D$ = diameter of the "projectile" (in cm)
- $V$ = impact velocity of the "projectile" (in m/s).

According to this formula, a thickness of 0.3 m (reinforced concrete or prestressed concrete) is sufficient to prevent the penetration of a "projectile" (600 mm diameter, 1500 kg weight, impact velocity 93 m/s).

In 1977 the French organizations EDF (Electricité de France) and CEA (Commissariat à l'Energie Atomique) published a formula \[3-16\] which likewise relates to the "penetration resistance" of reinforced concrete (for vertical hit). This formula is as follows (with the units kg, N and m for mass, strength and length respectively):

$$\frac{\rho \cdot V^2}{f'_c} = 1.7 \left[ \frac{\rho \cdot d^2 \cdot D}{G} \right]^4$$

where $\rho$ denotes the density of the concrete.

Apart from the density, the quantities in this formula are the same as in the preceding one. Hence it is relevant to compare the FIP-EMPA formula with the EDF-CEA formula (fig. 16).

Neither formula takes account of the quantity of reinforcement. The projectile firing tests on which the French formula is based have,
however, shown the reinforcement quantity to have virtually no effect, provided that it is at least 50 kg per m³ of concrete.

The wall thickness d in the EDF-CEA formula relates to the case where the projectile just penetrates the concrete ("juste perforation"). Penetration can therefore be entirely obviated by making the wall somewhat thicker than this calculated value. This extra thickness is determined with the same formula, but now substituting for V at least 114% of the impact velocity [3-16].

In the French firing tests it emerged that the "penetration resistance" of prestressed concrete is indeed superior to that of rein-
forced concrete. For prestressed concrete the minimum required wall thickness can be calculated with the EDF-CEA formula into which not more than 80 - 90% of the impact velocity need be adopted for V. The French experts consider this reduction to be justified, provided that the prestressed concrete wall in question is equipped internally with a metal liner. (Quite a few difficulties are likely to be encountered if a liner is installed, not in, but against a concrete wall; see 4.5). If no such liner is installed, the reduction will be no more than 5 - 10% [3-16].

As the available research results are as yet too few, EDF and CEA decided not to apply any reduction to prestressed concrete for the time being. The penetration resistance of prestressed concrete is therefore provisionally taken as equal to that of reinforced concrete, which in many cases will constitute an extra margin of safety.

When a "projectile" or some other hard object hits a relatively thin concrete wall, so-called "spalling" may occur on the rear of the wall, i.e., a somewhat conically shaped fragment of concrete is dislodged and hurled away at fairly high velocity (fig. 17). If this happens to a safety wall around a tank, the spalled-off fragment will hit the wall of the storage tank proper: obviously the gap between the safety wall and the tank wall will do nothing to stop this. If spalling occurs at the inner face of the outer tank of a double-walled tank, the insulating material in the cavity between the outer and inner tank walls will have a considerable retarding effect.

![Fragment of concrete dislodged by impact](image)

**Fig. 17.** Spalling effect at inner face of a relatively thin concrete wall on being struck by a "projectile" or other hard object
What measures can be taken to prevent the spalling effect is still a subject of research. It is fairly certain, however, that steel fibre concrete (see 3.5) offers promising possibilities with regard to this. This material is characterized by its high impact resistance, because the fibres contained in it are able to absorb much energy (energy dissipation).

3.7 Axial compressive and tensile impact loads

Fragments hurled away in an explosion, "projectiles", etc. (see 3.6) will, on hitting a solid surface, cause an "impact", more or less perpendicular to that surface. However, in cylindrical structures for "unpressurized cooled storage" certain causes may also set up axial impact loads acting, for example, centrally within the wall. These loads may consist of compression waves as well as tension waves.

Since concrete is a material possessing a high compressive strength, it is well able to resist compression waves (compressive impact loads). The presence of reinforcement or prestress in the concrete has little effect on this load-resisting capacity. Reinforcement and prestress are, however, important with regard to tension waves (tensile impact loads): reinforced concrete and especially prestressed concrete are well able to resist such waves. This does, however, require a correct ratio between the steel and concrete cross-sectional areas and good bond between the two materials.

The capacity of (otherwise unloaded) prestressed concrete to resist tensile impact loads has more particularly been studied in connection with the driving of concrete piles [7–12]. During the piling operations, tension and compression waves are set up in the longitudinal direction of the pile. The blow delivered by the pile hammer causes a compressive stress wave which travels at high velocity from the head to the toe of the pile. If the toe is in (very) firm soil, the compression wave will be reflected as a compression wave travelling back to the head of the pile. For a concrete pile this compression wave travelling up and down will cause few if any problems. In practice, however, the subsoil is more likely to be soft, so that the
toe of the pile will settle some distance into the ground when the compression wave arrives. In consequence, the wave now travels back upwards as a tension wave.

In reinforced concrete piles these tension waves will often cause cracking of the concrete, in which case the reinforcing steel must ensure that the tension waves will be transmitted across the cracks. To achieve this, the cross-sectional area of the reinforcement should be large enough to ensure that the stresses in it will remain below the yield point, so that no yielding of the steel will occur.

In prestressed concrete piles the above-mentioned tension waves are much less likely to cause cracking in the concrete. The latter is, after all, under considerable compressive stress (the "prestress"), so that its tensile strength is increased, as it were. Should cracks nevertheless occur, the tension wave will still be transmitted through the prestressing steel. As soon as the wave has passed, the prestress will cause the cracks to close up.

3.8 Temperature variations

Temperature variations may occur in concrete structures for "unpressurized cooled storage". For a proper understanding of the effect of such variations (see 3.8.2 and 3.8.3) it is necessary to have a clear conception of the thermal behaviour of concrete.

3.8.1 Thermal behaviour of concrete

The coefficient of thermal conductivity $\lambda$ of a material indicates the rate of heat conduction through that material. For concrete the value of $\lambda$ is approximately $2 \text{ W/m}^0\text{K}$, which is a fairly high value in comparison with that of other stone-like materials, but low when compared with the thermal conductivity of most metals.

Obviously, the dimension of the material in the direction of heat flow also plays a part in determining the amount of heat that is conducted. A criterion for this is provided by the thermal resist-
The thermal resistance of a material is given by the expression $R = \frac{d}{\lambda}$, where $d$ denotes the dimension concerned. This resistance increases in direct proportion to $d$, so that the thermal resistance of a 0.4 m thick concrete wall is twice that of a 0.2 m thick concrete wall.

What has been said above is, however, valid only for steady-state heat conduction, i.e., for constant temperature conditions, whereas in reality the temperature is liable to vary. For unsteady-state heat conduction the thermal behaviour will have to be characterized by other parameters.

The rate at which temperature variations penetrate into a material can be indicated by means of the thermal equalization coefficient $a$ of the material. For concrete this coefficient is approximately $1 \times 10^{-6} \text{ m}^2/\text{s}$. In comparison with other materials, it calls for much the same comment as that already made with regard to the conductivity coefficient $\lambda$. In connection with this aspect of the thermal behaviour of structures the dimension $d$ obviously here also plays a part. A measure for this is provided by the thermal inertia coefficient $E = \frac{d^2}{a}$. The value of $E$ increases proportionally to the square of the dimension $d$, so that in a 0.4 m thick concrete wall it takes four times as long for a particular temperature change to penetrate as it does in a concrete wall 0.2 m in thickness.

A concrete wall of some thickness possesses a high "buffering capacity", i.e., temperature variations in the environment penetrate only at a slow rate and with considerable time lag. This thermal property is particularly favourable for concrete structures which are exposed to radiant heat for some time (e.g., radiation from a nearby fire or the contents of a tank which have caught fire). The radiated heat will penetrate only slowly into the structure, so that the reinforcing steel or the prestressing steel in the concrete will be protected from (too) high temperatures (see 3.8.2). The same thermal property may, however, be rather unfavourable to concrete structures which are suddenly cooled on one side only (e.g., by outflow of cold liquid) (see 3.8.3).
3.8.2 One-sided heating by radiant heat

Concrete structures for "unpressurized cooled storage" may be exposed to one-sided thermal radiation. In this context it is not just the sun's rays, but also the heat radiating from a fire in the vicinity or from the burning contents of an adjacent tank, that must be considered. This heat transmitted by radiation will gradually penetrate into the concrete, though slowly and with a time lag (see 3.8.1). The longer the concrete is exposed to radiation, the more heat will it absorb.

Obviously, the temperature will rise first at the surface upon which the radiation falls. This will cause a temperature difference in relation to points located deeper within the concrete. However, this difference will diminish according as the concrete has been exposed to the thermal radiation for a longer time. Since the temperatures are subject to variations, this is clearly a case of unsteady-state heat flow through the concrete. The temperature distribution in the structure, as a function of time, can in principle be determined with Fourier's differential equation, which contains the thermal equalization coefficient (see 3.8.1).

If the heat radiation intensity is known, it is thus possible to determine the temperature distribution through the thickness of, for example, a concrete wall exposed to radiant heat. If the temperature distribution is non-uniform, it will cause strains (deformations) within the concrete; if these are wholly or partly restrained, i.e., prevented from developing, stresses will be set up, which can be calculated.

A reinforced concrete and, even more so, a prestressed concrete structure is well able to withstand one-sided heating by thermal radiation, provided that such structures have been correctly designed and detailed. In this connection it is necessary, among other matters, to pay due attention to the "concrete cover" on the reinforcing steel or pre-stressing steel, because the high "buffering capacity" of concrete (see 3.8.1) can, if the cover is sufficient, protect the steel against excessive rises in temperature for a long time.
If the contents of a storage tank catch fire, the blaze that occurs above the liquid surface level will have a temperature of many hundreds of degrees Centigrade. If the tank wall is of prestressed concrete, a large number of continuous (through-and-through) cracks will form in the part of the wall above the surface of the liquid. All the same, this part will remain more or less intact on account of the bond of the steel to the concrete in the portions between the cracks. Below the liquid surface the prestressed concrete wall will remain completely liquid-tight, provided that the prestress continues to be effective there. This latter condition requires that the prestressing steel and the reinforcing steel should be bonded to the concrete over the entire length of the tendons or bars concerned.

The correct designing and detailing of the prestressed concrete walls envisaged here (tank walls, safety walls, etc.) must ensure that the cracks caused by temperature differences do not penetrate too deep into the wall and that the steel in the wall does not reach the "critical temperature".

### 3.8.3 One-sided cooling by cold liquid

Concrete structures for "unpressurized cooled storage" will undergo one-sided cooling if they come into contact with cold liquid (or cold gas). During the filling of a concrete storage tank this cooling can be controlled by employing the correct filling procedure ("cool-down operation"), so that the tank wall is not subjected to a too-rapid fall in temperature.

A rapid temperature drop will inevitably occur if a quantity of cold liquid suddenly "hits" a concrete wall, e.g., as a result of leakage from a storage tank or in the event of damage or indeed collapse of the tank. On first contact, heat will be extracted from the concrete, so that evaporation of the liquid takes place. After this, the cooling of the concrete will proceed more slowly (see 3.8.1), probably also because the thin layer of gas which forms between the liquid and the concrete wall can have an insulating effect.
Fig. 18. Calculated temperature distribution, as a function of time, in a 0.4 m thick concrete safety wall suddenly exposed to liquid natural gas (LNG); the (favourable) effect of the so-called interfaces has been taken into account [8-2]
The "contact" surface will obviously first undergo a fall in temperature. When that happens, a considerable temperature difference with regard to points located deeper within the concrete will develop. This difference will decrease with increasing length of time of the cooling action, but may at first give rise to surface cracking in the "concrete skin". The presence of steel fibres (see 3.5) in the concrete could have a particularly favourable effect under these circumstances.

Actually, with one-sided cooling the same kind of thing happens as with one-sided heating (see 3.8.2), except that the direction is reserved. Accordingly, for this unsteady state the temperature distribution in the concrete can be determined as a function of time with the aid of Fourier's differential equation, provided that the boundary conditions are known. Other methods of calculation are also available for the purpose.

By way of example, fig. 18 shows the results of calculations for a 0.4 m thick concrete safety wall which is suddenly exposed to LNG (liquefied natural gas) [8-2]. It appears from this diagram that, after half an hour, there occurs a temperature difference of about 130 °C through the first 40 - 50 mm of wall thickness, which constitutes an extremely severe temperature loading for this "concrete skin". In the foregoing it has already been pointed out that the presence of steel fibres (see 3.5) could be particularly advantageous under these circumstances. It furthermore appears from the diagram that a steady state has been established after 64 hours. When this has been achieved, there exists a temperature difference of about 135 °C through the full 0.4 m thickness of the concrete wall, at least if the effect of the so-called boundary layers is neglected, as has been done in fig. 18.

The temperature distribution associated with sudden one-sided cooling has also been determined experimentally, inter alia, for the experimental tank at Nantes in France [6-19] and for test slabs in the Federal Republic of Germany [3-6]. In those tests, more particularly the German ones, good agreement between the measured and the calculated values was found. A non-uniform temperature distribution through the
thickness of, for example, a suddenly cooled concrete wall will give rise to strains in the concrete which, if wholly or partly restrained, will cause stresses. Such stresses, which can be calculated in principle, may crack the concrete. If it occurs, such cracking will of course manifest itself on the face of the wall where the concrete tends to contract, i.e., where it cools.

In order to prevent such cracks from extending through the full thickness of the wall, it is necessary to take appropriate precautions in the design of the structure. In this respect, too, prestressing the wall is the most effective measure. A prestressed concrete structure is able to withstand one-sided cooling by cold liquid, provided the structure has been correctly designed and detailed. The thickness of the uncracked zone can be predetermined by suitably choosing the magnitude and the location of the prestress.

As appears from measurements and calculations, the rate of cooling is highest directly under the cooled surface. In the outer "shell" (the "concrete skin") fairly large temperature differences can therefore be expected to develop quickly. The stresses due to these could cause "spalling" of the concrete. From tests performed in the Federal Republic of Germany [3-6], the Netherlands [8-2], France [6-19] and elsewhere, it emerges that this does not happen, however. Superficial cracking does indeed occur in the "concrete skin", but there is no question of spalling. This favourable behaviour is perhaps bound up with the fact that the cold liquid, on first contact with the concrete, undergoes (rapid) evaporation. The thin layer of gas which, as a result, forms between the cold liquid and the warmer concrete wall could have an insulating effect. This would slow down the rate of heat extraction from the concrete and make it last a long time, which is something that could be expected also on account of the high "buffering capacity" of concrete (see 3.8.1). Under these conditions a considerable amount of gas evolution is liable to occur for a long time, possibly giving rise to overpressure of the gas in an enclosed space.

At normal temperatures (about 20 °C) concrete and steel (reinforcing steel or prestressing steel) have the same coefficient of thermal
expansion. In the Netherlands code of practice VB 1974 (NEN 3861) [1-4] the value of this coefficient is given as \(12 \times 10^{-6}\) per \(^\circ\)C for both materials. However, at lower temperatures this coefficient decreases less for steel than it does for concrete (see 3.1.2.1 and 3.2.3), i.e., the cooling contraction of steel is greater than that of concrete. In a cylindrical prestressed concrete wall this will cause an increase in steel stress and therefore an increase in the prestress it produces in the concrete, which is of course favourable.

3.9 Choice between reinforced concrete and prestressed concrete

Although the "design aspects" are dealt with mainly in Chapters 5 to 9, it is desirable to conclude this chapter with a closer look at the arguments which may decide in favour of prestressed concrete and/or the rejection of reinforced concrete for structures intended for "unpressurized cooled storage". In this context it is chiefly that walls that have to be considered: tank walls and safety walls.

3.9.1 Ordinary conditions during use

In consequence of liquid load the wall of a tank is in a state of tensile loading. The tensile forces associated with this are so large that a reinforced concrete wall would have to have very massive dimensions, at least if no cracks are to be allowed in it in order to ensure liquid-tightness.

Example: storage tank of 50 m diameter, height of liquid 25 m, density of liquid 0.6; tensile force at base of tank wall 3750 kN per metre length; thickness of wall has to be 2.5 m if the tensile stresses in the concrete are to be limited to 1.5 N/mm\(^2\).

The tensile stresses in the concrete have to be kept down to not more than 1 - 1.5 N/mm\(^2\) in order to avoid the risk of cracking of the wall. To fulfill this condition would necessitate an unacceptably thick wall. This thickness can be limited either by allowing cracks (not exceeding a certain width) in the reinforced concrete or by placing the wall under a certain compressive stress, i.e., prestressing it.
With a prestress of, for example, 7.5 N/mm\(^2\) the concrete wall will in any case be able to resist a tensile force of the same magnitude without this causing any tensile stress in the concrete. In the above example this prestress would reduce the thickness of the wall to 0.5 m.

Besides, fairly high tensile stresses are liable to occur in the concrete already in the **construction stage** of the wall - especially, quite soon after concreting. This is due to various factors such as shrinkage of the concrete and - more particularly in walls of substantial thickness - non-uniform temperature distribution through the wall.

A prestressed concrete wall starts off with an advantage in this respect because it is thinner than an equivalent wall built of reinforced concrete. Furthermore, the prestress can be applied at an early point in time, by tensioning the tendons in two or more stages if necessary, so that the undesirable tensile stresses in the concrete are limited or eliminated and the wall will therefore not crack.

On the other hand, a reinforced concrete wall will often develop cracking even before it is put into service. Under the action of its working load due to the liquid it retains, such a wall will always be cracked (unless it is made exceedingly thick).

The presence of cracks in a concrete wall will adversely affect its liquid-tightness (particularly in consequence of vertical cracks extending all the way through the thickness of the wall), while the inherently rather limited gas-tightness of the concrete will be further reduced. Besides, the proper connection of steel liners to the inside of a tank wall will become very difficult if the wall contains cracks that have to be "bridged". The same can be said of coatings made of plastic or similar material which have to be completely bonded to the concrete surface and with which it is likewise awkward to bridge over the cracks, as this requires a relatively very large amount of stretch in the plastic at the crack (fig. 19).
For "unpressurized cooled storage" structures a further drawback of reinforced concrete is the fact that reinforcing steel is not directly very suitable for use at low temperatures (see 3.2.2). Generally speaking, storage tanks for (cold) liquids should, if constructed of concrete, always be prestressed.

When a concrete storage tank is being filled with a liquefied gas, the cooling of the structure can be so controlled as to take place in a gradual manner by applying the correct filling procedure ("cooldown operation"). In this way the development of (too) high tensile stresses in the concrete, due to non-uniform temperature distribution through the thickness of the wall, can be suitably curbed. In actual practice the cooldown periods are sometimes curtailed, mostly for economic reasons. In such cases there are indeed likely to be excessively high tensile stresses in the concrete wall. In this respect, too, reinforced concrete is unsuitable, since these tensile stresses will cause (additional) cracking in the wall.
As contrasted with tank walls, safety walls are not subjected to liquid pressure under normal service conditions. Such walls could, in so far as this is concerned, be built of reinforced concrete. Whether this is indeed practicable will depend on the requirements applicable to such walls under special circumstances (see 3.9.2).

3.9.2 Special conditions during use

Liquid-retaining concrete walls will in principle always have to be prestressed (see 3.9.1). Prestressing is moreover desirable because a prestressed concrete tank will never suddenly "split open" ("zip"), even in the event of brittle fracture of a prestressing tendon, because compressive stress is maintained everywhere in the concrete, so that no local cracking can occur in it (see 3.9.3). A reinforced concrete wall is more "critical" in this respect.

A concrete wall should also remain intact under the consequences of an "undesirable event of external origin": a nearby fire, an explosion in the vicinity, flying fragments, sabotage, crashing aircraft, natural phenomena, etc. (see 2.3.2). Under such circumstances there is indeed a difference in behaviour between reinforced concrete and prestressed concrete, but this difference is often not so great as to warrant the choice in favour of prestressed concrete for this reason alone.

Safety walls could therefore be of reinforced concrete. When such a wall, in the event of a disaster, has to function as a second line of defence in retaining the liquid, it will be subjected to a "liquid impulse" and also to a considerable fall in temperature. Under these influences a reinforced concrete wall is bound to crack, both vertically and horizontally. Whether such cracking is acceptable will depend on the requirements as to liquid-tightness that the wall must fulfil (and these will usually be quite stringent ones) or on the presence of an additional line of defence in the form of, for example, an earth-banked wall. Besides, continuous (through-and-through) vertical cracks which open up abruptly are liable to cause local fracturing of the reinforcement, with the attendant risk of
continuing brittle fracture of the reinforcing bars in those cracks. If reinforced concrete construction is nevertheless employed, the reinforcing steel to be used should be carefully investigated with regard to this possibility of brittle fracture.

Cracks will inevitably occur at the inner face of a safety wall as a result of sudden contact with cold liquid in the event of a disaster. The width and the depth of such cracks can be restricted by correct design of the prestress in terms of its magnitude and location. Its magnitude should be such that it will not be neutralized by the liquid pressure ("liquid impulse"). This extra amount of prestress ensures that cracks will not extend all the way through the wall, i.e., an uncracked zone will remain at the outer face of the wall.

If a storage tank fails, a powerful tensile impact load will occur in the concrete wall surrounding this tank. This impact will often be so severe as to cause the tensile strength of the concrete to be exceeded in a prestressed wall, even if it has been provided with a substantial extra prestress, so that cracks are formed. The extra amount of prestress that can be applied in practice will, incidentally, be limited by the amount of space available within the thickness of the wall for accommodating the tendons, anchorages, etc. and by the compressive strength attained by the concrete.

For these reasons the stresses in the prestressing steel should be of such magnitude that, under the influence of the above-mentioned tensile impact load - which has to be transmitted by the prestressing steel across the cracks - the strains in the steel remain entirely within the linear elastic range of behaviour. After the impact has passed, the cracks will be closed up by the prestress, so that the liquid-tightness of the wall is preserved. The extra prestress will of course furthermore have to ensure that there will be no through-and-through cracks in the wall under liquid loading either.

If a storage tank fails, the second line of defence (mostly a safety wall) will first be subjected to a "liquid impulse" and will only then
undergo a rapid fall in temperature. When the tensile impact load occurs, more particularly the prestressing steel will not yet have acquired a low temperature.

Reinforced concrete walls are sometimes used for underground storage tanks (see 4.11) on the assumption that the earth pressure puts such walls under prestress. This prestress is indeed present, except when the walls contract on cooling and are then — for a time anyway — deprived of the earth pressure.

Besides, these reinforced concrete walls will be completely cracked as a result of liquid and temperature loading. Also, the earth pressure cannot prevent the formation of horizontal cracks, so that the cold liquid can penetrate into the surrounding soil and evaporate there.

### 3.9.3 Possibility of sudden failure of a concrete tank

The failure of a storage tank, more particularly by "ripping open", (also called "zipping effect") is treated as an "undesirable event of internal origin" in this report (see 2.3.1.4). In steel tanks, even when constructed of special steel, such phenomena cannot be entirely ruled out. What can be said of concrete tanks in this respect?

In seeking the answer to this question a distinction should be drawn between reinforced concrete and prestressed concrete. The considerations relate to a liquid-retaining wall which, depending on the type of structure, has already entirely or partly assumed the temperature of the cold liquid.

### 3.9.3.1 Reinforced concrete wall

A free-standing reinforced concrete wall is not by itself able to be completely liquid-retaining, as it will contain vertical and horizontal tensile cracks (see 3.9.1 and 3.9.2). Even if it is pre-
supposed that it should be possible to ensure the desired liquid-tightness (and gas-tightness) by means of special sealing layers (liners, etc.), a reinforced concrete wall is still not fully reliable. For if a reinforcing bar should fracture at a crack, from whatever cause, it cannot be ruled out that the resulting impact-like jerk will in turn cause other reinforcing bars, likewise loaded to a high steel stress, to fracture at that crack as well. Thus, a series of bar fractures could be initiated, resulting in a phenomenon closely resembling the so-called "zipping effect" in steel tanks, though less rapid. This possibility should be given due consideration in a case where the use of reinforced concrete for free-standing or earth-banked tank walls is contemplated. Besides, continuous vertical tensile cracks in the wall are liable to initiate "brittle fracture" processes in the reinforcement (see 3.9.2).

3.9.3.2 Prestressed concrete wall

The following can be said with regard to the condition of a prestressed concrete wall under working load conditions:

- The wall is always under compressive stress, even when the tank is full, as there must always be some extra prestress as a reserve. The concrete wall is therefore uncracked.

- The prestressing steel is tensioned and fully embedded in hardened concrete or hardened grout. Because of this embedment and bond, no relative movements between this steel and the concrete can occur, and mechanical damage to the steel is therefore not possible either.

- Like the prestressing steel, the anchorage elements embedded in the concrete, grouted and provided with a sealing finish, are in a state of rest.

Therefore no fracturing of tendons can be expected to occur under working load conditions, i.e., the conditions of normal service of the structure. A practically uniform stress distribution exists throughout the tank wall. There are nowhere any stress concentrations at cracks, etc. Although prestressing steel may be somewhat more
susceptible to damage (see 3.2.3), in this stage that is not im-
portant, since no detrimental influences can occur in properly
constructed structures.

The "ripping open" of prestressed concrete tanks can therefore be
completely discounted, inasmuch as no cracks can form in the concrete
maintained under compression by the prestress. All the same, it tes-
tifies to a sense of reality to assume even under such circumstances
that a tendon may fracture, unlikely though that is.

If a local fracture of a tendon occurred, nothing untoward would
happen in the prestressed concrete wall, for the following reasons:

- The tendon is completely embedded in hardened grout or hardened
concrete. The supposed tendon fracture cannot spread to adjacent
tendons because there is no direct connection to them, and indeed
not through the concrete, since this remains uncracked (and under
compression). The fracturing of the tendon will scarcely cause a
jolt or shock in the structure; besides, any effect that this
could have cannot be transmitted - as "impact" - to the adjacent
tendons via a crack extending across all the tendons.

- The concrete around the tendons is entirely under compression and
remains under compression on account of the extra (reserve) pre-
stress provided. Hence no propagation of a crack in the concrete
can occur from the point of fracture of the tendon.

- Thanks to the bond between the prestressing steel and the concrete,
the tensile force in the tendon is fully built up at only a short
distance from the fracture. The concrete under compression "bridges"
the fracture and restores the steel stress directly adjacent to it.

Note: In the case of unbonded tendons, i.e., not bonded to the struc-
tural concrete by grouting or direct embedment, a fractured
tendon will lose all its stress over the entire length between
two anchorages, so that in such circumstances the above-mentioned
"bridging" effect will not be obtained. This is one of the reasons
why unbonded prestressing steel is not suitable in all those
cases where the problem envisaged here is liable to occur.
3.10 **Insulating materials**

Although this chapter is concerned with the behaviour of concrete and concrete structures, for the sake of completeness some information on the insulating materials that may be used in connection with the structures under consideration will be given here.

With regard to these materials it is necessary to distinguish between:

- insulating materials in granular form \((I_p)\);
- coherent insulating materials, applied in the form of blankets \((I_c)\), blocks \((I_b)\) or layers \((I_s)\).

3.10.1 **Insulating materials in granular form \((I_p)\)**

The granular insulating materials are used more particularly in double-walled tanks, between the inner and the outer tank. One of the most extensively used products is perlite, an expanded mineral. When filling an insulating cavity with a material of this kind, it must be ensured that no voids are formed in the insulation. All the same, after a time a certain amount of consolidation will occur in the loosely packed granular material. When that happens, additional material will have to be packed into the cavity. During filling, but also during the subsequent consolidation, frictional forces will develop between the tank walls and the insulating material. In order to limit these forces, the walls, especially steel ones, should be provided with a sliding layer.

3.10.2 **Coherent insulating materials (loadbearing insulation)**

As contrasted with the granular insulating materials (see 3.10.1), the "coherent" thermal insulators are able to transmit loads and can therefore be classed as "loadbearing". The magnitude of the transmissible loading will of course depend on the strength properties of such materials. Thus, glass-wool blankets \((I_c)\) can take only very little load, whereas foamed glass blocks \((I_b)\) have a substantially higher load capacity.
PVC slabs were used for insulating two single-walled concrete tanks for LNG at Montoir-en-Bretagne, France [8-9]. Such slabs can be assigned to the category of "insulating materials in the form of blocks" (I_b).

The insulating materials to be applied in one or more layers (I_s) are usually sprayed onto the surface to be insulated. The products developed for the purpose, based on polyurethane, include "Pur" (Bayer) and "Puf" (Shell).

With regard to the application of layer-type insulating materials (I_s) there should be proper certainty that they will adhere firmly to the surface. This will have to be verified by means of tests. In order to obtain good adhesion (bonding), it may be necessary to give the surface a preparatory treatment, e.g., by mechanical means. Also, a so-called primer (bonding layer) may be used, while bars anchored in the concrete wall are employed for resisting tensile forces.

Provided that they are carefully applied, the layer-type materials (I_s) will be liquid-tight and vapour-tight, or only liquid-tight, depending on the product concerned. What degree of tightness (impermeability) will be available is something that must be duly ascertained before the insulating material is applied. There should also be reliable information on the magnitude of the loading that the material can transmit.

3.10.3 Review of available insulating materials

Table 5 gives a review of the available thermal insulators [5-1]. As the compiler points out, the data listed in the table have not been verified, while some data are lacking. Accordingly, this table is presented here only for general information and preliminary orientation. When any particular insulating material is used, it will indeed often prove necessary to investigate its properties more closely.
Table 5. Summary of available insulating materials [5-1]

<table>
<thead>
<tr>
<th></th>
<th>density (kg/m³)</th>
<th>compressive strength (N/mm²)</th>
<th>coefficient of thermal conductivity at approx. +10 °C (W/m.°C)</th>
<th>coefficient of thermal conductivity at approx. -80 °C (W/m.°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;inner tank insulation&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>expanded mineral (Perlite)</td>
<td>55 loose</td>
<td></td>
<td>0.041</td>
<td>0.030</td>
</tr>
<tr>
<td></td>
<td>65 densely packed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>glass fibre reinforced panels (Fiberglass)</td>
<td>22</td>
<td></td>
<td>0.034</td>
<td>0.023</td>
</tr>
<tr>
<td>mineral wool</td>
<td>approx. 35</td>
<td></td>
<td>0.030</td>
<td>0.023</td>
</tr>
<tr>
<td>&quot;outer tank insulation&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>foamed plastics (Styrofoam &quot;1b&quot;)</td>
<td>30</td>
<td>0.25</td>
<td>0.035</td>
<td>0.022</td>
</tr>
<tr>
<td>polyurethane (Polyurethane &quot;30&quot;)</td>
<td>30</td>
<td>0.25</td>
<td>0.030</td>
<td>0.026</td>
</tr>
<tr>
<td>&quot;Klegecell&quot; (&quot;33&quot;)</td>
<td>33</td>
<td>0.25</td>
<td>0.023</td>
<td>0.019</td>
</tr>
<tr>
<td>&quot;Klegecell&quot; (&quot;40&quot;)</td>
<td>40</td>
<td>0.40</td>
<td>0.023</td>
<td>0.019</td>
</tr>
<tr>
<td>&quot;loadbearing insulation&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>foamed glass (Foamglass)</td>
<td>135</td>
<td>0.65</td>
<td>0.052</td>
<td>0.043</td>
</tr>
<tr>
<td>foamed plastics (Styrofoam &quot;HD 300&quot;)</td>
<td>45</td>
<td>0.70</td>
<td>0.029</td>
<td>0.019</td>
</tr>
<tr>
<td>foamed plastics (Styrodur &quot;V 5000&quot;)</td>
<td>55</td>
<td>0.74</td>
<td>0.030</td>
<td>0.019</td>
</tr>
<tr>
<td>&quot;Klegecell&quot; (&quot;55&quot;)</td>
<td>55</td>
<td>0.55</td>
<td>0.026</td>
<td>0.019</td>
</tr>
<tr>
<td>&quot;Klegecell&quot; (&quot;75&quot;)</td>
<td>75</td>
<td>0.80</td>
<td>0.026</td>
<td>0.019</td>
</tr>
<tr>
<td>polyurethane (Polyurethane &quot;80&quot;)</td>
<td>80</td>
<td>0.65</td>
<td>0.029</td>
<td>0.025</td>
</tr>
<tr>
<td>foamed plastics (Styrofoam &quot;HD 1623&quot;)</td>
<td>53</td>
<td>0.88</td>
<td>0.030</td>
<td>0.022</td>
</tr>
<tr>
<td>MDC 3D insulation</td>
<td>74-84</td>
<td>0.9</td>
<td>0.027</td>
<td>0.030</td>
</tr>
<tr>
<td>balsa wood (parallel to grain)</td>
<td>145</td>
<td>4.0</td>
<td></td>
<td>0.098</td>
</tr>
<tr>
<td>balsa wood (across grain)</td>
<td>145</td>
<td>0.5</td>
<td></td>
<td>0.038</td>
</tr>
<tr>
<td>&quot;Perlite&quot; concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 : 2 ½ : 1 ½</td>
<td>1220</td>
<td>8.5</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>1 : 2 ½ : ⅟</td>
<td>1475</td>
<td>13.0</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>1 : 5</td>
<td>523</td>
<td>3.0</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>1 : 7</td>
<td>381</td>
<td>1.2</td>
<td>0.085</td>
<td></td>
</tr>
</tbody>
</table>
In conformity with the review as presented in the original publication, a distinction is drawn between:

- "inner tank insulation" (for double-walled tanks, between the inner and the outer tank);
- "outer tank insulation" (for single-walled tanks, on the outside, for storage temperatures above about -50 °C);
- "loadbearing insulation" (capable of transmitting loads).
STORAGE SYSTEMS AND FORMS OF CONSTRUCTION IN CONCRETE

4.1 General

Various systems are possible for "unpressurized cooled storage" as envisaged in this report (see 2.1). They have already been outlined in Chapter 2 (see 2.2).

In the present chapter a more detailed description is given of forms of construction based wholly or partly on the use of concrete as the structural material. These forms of construction are coded in accordance with a system intended for international use [2-14 and 2-17]. The following abbreviations are used in connection with this coding:

C = concrete, generally prestressed concrete, sometimes reinforced concrete;
S = steel, special steel or ordinary (carbon) steel, sometimes aluminium;
I = insulation cavity;
L = vapour-tight liner, of steel or some other material, sometimes in the form of a so-called membrane
(Note: if the liner is installed in the concrete, the abbreviation L is employed as a subscript: C_L);
-- = gap (annular space)

Various forms of construction in concrete are to be distinguished (see 4.3 to 4.10). For the sake of completeness, the double-walled and the single-walled steel tank have been included (see 4.2), although these do not involve concrete as a structural material except for the foundation and possibly for the surrounding catch basin wall. A general description of the various forms of construction is given in this chapter, ignoring the structural details, because they play only a minor part in this context. They are dealt with in Chapter 6.

For each solution the advantages and disadvantages are stated, insofar as these are of importance within the framework of the present
Fig. 20. Double-walled steel tank, with insulation between inner and outer tank (SIS)

Note: Other solutions are also possible for the structural details such as wall-to-base and wall-to-roof connections.
report. The treatment of the subject is based more particularly on the problems which may arise in connection with "unpressurized cooled storage", as outlined in Chapter 2.

4.2 Double-walled steel tank, with insulation between inner and outer tank (SIS) (fig. 20), and single-walled steel tank, with insulation on the outside (IS) (fig. 21)

The inner tank ("primary tank") is usually constructed of a special steel such as nickel steel because the properties of such materials, e.g., with regard to crack arrest, remain favourable at low temperatures. On the other hand, ordinary (carbon) steel is mostly used for the outer tank, since this structure, besides supporting the steel roof structure, only has to form the enclosure for the insulation surrounding the inner tank. The insulation cavity between the inner and the outer tank wall is generally about 1 m wide.

In order to avoid gas overpressure in the inner tank, the insulating cover to the top of this tank is permeable to gas. With the space above this cover (under the steel roof) in open communication with the insulation cavity there will be gas within the insulating material. There is no objection to this, as the presence of the gas does not impair the insulating function. Nor is there any risk of a combustible or explosive gas/air mixture being formed in this cavity, as the air needed for this is not available there. However, because of the presence of the gas in the cavity, the outer tank will have to be gas-tight. In an alternative type of design the contents of the inner tank are completely sealed off from the insulation cavity. In that case the insulation cavity is filled with nitrogen as a check for the gas-tightness of the inner tank.

In order to limit the area over which liquid flowing from the tank can spread in the event of leakage or structural failure, a double-walled steel tank is placed within a catch basin, i.e., an enclosure surrounded by a wall or earth bank. This basin must be able to accommodate the entire contents of the tank.
Fig. 21. Single-walled steel tank, with insulation on the outside (IS)

Note: Other solutions are also possible for the structural details such as wall-to-base and wall-to-roof connections

1 = carbon steel  
2 = steel roof structure  
3 = chrome-nickel steel (or aluminium)  
4 = concrete structure  
5 = perlite (or similar granular insulating material) \( I_p \)  
6 = foamed glass (or similar loadbearing insulating material) \( I_b \)  
7 = glass wool blanket (or a similar material) \( I_c \)  
8 = perlite concrete (or a similar material)  
9 = balsa wood (or a similar material)  
10 = rigid insulating material \( b_1 \)  
11 = aluminium  
12 = vapour-tight layer  
13 = liner (carbon steel)  
14 = vapour-tight and liquid-tight membrane (chrome-nickel steel or stainless steel)  
15 = heating pipe  
16 = joint structure  
17 = seal  
18 = pile (or column)  
19 = water discharge  
20 = rubber bearing
In the event of overfilling of the inner tank, liquid may enter the insulation cavity if the latter is in open communication with the inner tank. If that happens, the insulating function will be impaired because of the intense evaporation that will occur within this cavity under those circumstances. If the cold liquid comes into contact with the outer tank in consequence of overfilling or some other cause, the ordinary steel of which that tank is constructed will often prove inadequate to stand up to such conditions. It is of course possible to use a suitable special steel for the outer tank as well, but that is a more expensive solution.

A steel outer tank will, without special measures, generally not be very well able to withstand external influences, such as heat radiation from a nearby fire or explosion, flying fragments, sabotage activities, etc. Of course, precautions for improving the heat resistance and possible other properties of the outer tank to cope with such eventualities are possible. If the outer tank is seriously damaged by an external influence, the insulation will no longer properly be able to perform its function, so that the safety of the storage tank is no longer adequately ensured. The tank will then have to be pumped out to enable the damage to be repaired.

The catch basin formed by the enclosing wall or bank restricts the area into which the liquid can flow in the event of leakage or failure of the tank. If the containment area formed by the basin is large, evaporation and/or catching fire of the outflowing liquid may result in major disasters (see 2.4).

A structural aspect deserving close attention in the double-walled steel tank is the manner in which the roof structure is supported. In certain cases, partial damage of the outer tank may result in collapse of the roof, with all the attendant consequences thereof. A special resilient layer is interposed between the walls of the two steel tanks and the insulation. This resilient layer forms part of the insulation system and is, inter alia, necessary for limiting the magnitude of the forces exerted upon the walls as a result of the subsequent consolidation on cooling ("cooldown") and on warming.
Fig. 22. Double-walled steel tank, with insulation between inner and outer tank, and surrounded by a concrete safety wall (C—SIS)

Note: Other solutions are also possible for the structural details such as wall-to-base and wall-to-roof connections.
up (see 3.9.1). The thickness of the insulation is determined by the temperature of the stored liquid.

For the storage of substances with a less low boiling point, single-walled tanks may be used as an alternative to double-walled tanks. Constructed of suitable steel, the single wall is provided externally with an insulating layer enclosed by a thin "skin" of ordinary (carbon) steel or of aluminium (IS) (fig. 21).

4.3 Double-walled steel tank, with insulation between inner and outer tank, and surrounded by a concrete safety wall (C—SIS) (fig. 22)

The double-walled steel tank (SIS) may be provided with a free-standing safety wall. Such a wall, which is usually constructed of prestressed concrete, possesses a number of properties intended to enhance the safety of storage. In the event of failure of the tank enclosed within the safety wall, the latter will restrict the area of burning or evaporating liquid. To perform this duty, the safety wall should be capable of resisting the forces to which it is subjected in the event of sudden outflow of liquid from the tank, such as "liquid impulse" and "temperature change". This is an important reason why it is often essential to use prestressed concrete (see 3.9).

The safety wall therefore also functions as a second liquid-retaining structure, and a wall or bank to form a catch basin around the tank can be dispensed with. Because of this, tanks can often be placed closer together (clear distance approximately 1.25 times the tank diameter) than if a catch basin were provided. A safety wall also effectively protects the enclosed tank from external influences. A wall of this type is of course higher than the containment wall or bank of a catch basin, so that, in the event of fire in an adjacent installation, the heat radiation to which the tank wall and, to a less extent, the tank roof is exposed will be restricted.

"Gap problems" - Problems of the annular space

For technical reasons of construction the safety wall will always
be located some distance from the double-walled steel tank. To some extent contradictory requirements are applicable to this width of the "gap", i.e., the annular space between the tank and the safety wall.

**Explosion**

Gas can get into the gap in consequence of leakage (from pipes, valves, etc.). With the air present in the gap, the gas can form a "critical" gas/air mixture which is combustible and/or explosive. The gap is a semi-closed space, as its height is very much greater than its width, and in this respect it constitutes an "ideal explosion space". Now if there is a "critical" gas/air mixture, it may explode from any one of a variety of causes, such as lightning. It has hitherto been widely assumed that an explosion of this kind may produce an overpressure of the order of 0.2 - 0.3 bar. For each individual case the explosion pressure liable to develop can be approximately determined with the aid of information published in the literature.

During and after an explosion of the gas mixture in the gap the steel outer tank and the concrete safety wall should remain intact. A steel outer tank will therefore have to be strengthened with stiffening ribs, etc. in order to prevent it from buckling in consequence of this explosion pressure.

**Detection**

The presence of gas in the gap can be detected with the aid of gas detectors installed in it (sniffers, sniffing heads or sensors). As soon as these devices give warning that the so-called threshold value has been exceeded, counter-measures can be taken. An obvious method is to pump out the gas from the gap, which of course requires appropriate equipment. A better solution would appear to consist in blowing an inert gas, heavier than the combustible gas, into the gap. In connection with LNG storage installations, nitrogen is more particularly suitable for such "inertization". For blowing the inert gas into the gap, the latter has to be provided with a ring main.
Alternatively, air may be blown in, at least in cases where the combustible gas in the gap is lighter than air. The drawback of this method is that it could in fact cause a "critical" gas/air mixture to be formed. Another way to get rid of the gas in the gap is to ventilate the latter. Besides, ventilation is usually desirable for controlling the temperature in the gap. Forced-draught ventilation, i.e., produced by mechanical means, is appropriate for the purpose.

Experience gained in actual practice has shown that natural ventilation is also quite possible, but requires a fairly wide gap, e.g., with a width at least equal to one-tenth of the height.

**Accessibility**

The gap between the tank and the safety wall must be properly accessible to enable the external wall of the actual storage tank to be inspected. Accessibility requires a sufficiently wide gap, e.g., its width should be not less than one-tenth of its height, with a minimum of 1.5 - 2 m. Frequently, however, it will be considered an unacceptable hazard to allow personnel to descend into a "slot" of such width and a height of, say, 30 m. It therefore appears likely that the Industrial Inspection authorities in the Netherlands will in future object to the construction of such narrow gaps around tanks.

**Outflow of contents of tank**

Hence there are various reasons for choosing a fairly wide gap. Against this, however, it appears desirable to make the diameter of the safety wall as small as possible, for in this way the space into which the liquid can escape in the event of leakage or failure of the storage tank is restricted. Also, a gap of minimum width is found to be preferable from the viewpoint of the loads to which the safety wall is subjected when liquid flows out of the tank, namely, "liquid impulse" and "temperature shock". The loading upon the safety wall is liable to be particularly severe in a case where the tank ruptures suddenly.
The magnitude of the load ("liquid impulse") depends on the width of the gap, so that for this reason, too, it is necessary to limit its width. In this connection it should also be borne in mind that the tank may undergo displacement in the direction opposite to that of the wave of liquid issuing from the ruptured tank wall. This may cause the tank, still largely filled with liquid, to strike against the safety wall. When the damaged tank discharges its contents into the gap, the liquid comes into contact with the concrete safety wall, which possess a high thermal capacity. Because of this, very intense evaporation will occur for a considerable time, so that a large cloud of gas will be formed.

Fire

In the event of a fire, the gap must never be filled with fire-extinguishing water, because the steel outer tank has not been designed to withstand the hydrostatic pressure that would then be exerted upon it. For the same reason the inner tank must not be subjected to external pressure, e.g., due to water. Although this tank is filled with liquid, the latter is lighter than water, so that the presence of water around it may, in certain cases, result in an externally acting compressive loading. This can be more particularly serious if the inner tank is not completely filled or if it has to be emptied quickly in an emergency.

Rainwater

The problems from rainwater can be the same as those caused by fire-extinguishing water. They could be prevented by designing the roof structure so as to extend over the gap and thus shed the rainwater outside it. Quite often this solution is not a practicable one, however. This is certainly so in a case where the safety wall is higher than the storage tank. Such extra height of the safety wall is provided in order to obviate "negative" forces (suction forces) acting upon the roof, e.g., due to wind or to an explosion in the vicinity of the tank.
If the safety wall is higher than the tank it surrounds, the gap may be provided with a separate roof structure of its own. But this solution has the disadvantages of poorer accessibility, poorer ventilation and a higher risk of the formation of a "critical" gas/air mixture. Besides, if the tank suddenly spills its contents into the gap, sudden gas formation will occur as a result of the liquid coming into contact with the safety wall, so that the roof is liable to be blown away very soon.

**Water discharge**

The gap between the tank and the safety wall will therefore usually require arrangements for the discharge of any water that gets into the gap. So-called manholes (water outlets) equipped with valves are sometimes provided in the outer tank. The materials used for these features should be resistant to low temperatures so as to remain intact in the event of coming into contact with cold liquid or cold gas.

Alternatively, sumps may be provided, from which the water is removed by pumping it through a pipe passing over the wall. For combating a possible outbreak of fire in the tank, but more particularly for protecting the tank against heat radiation from an adjacent fire, a sprinkler installation may be mounted on the outside of the safety wall and on the roof. If this installation comes into operation, water may get into the gap, but this will seldom cause problems, since the greater part of the water sprayed from the sprinklers will evaporate.

For the sake of completeness it should be pointed out that an undesirable reaction may occur between water and gas that enters the gap. Some gases may produce toxic reaction products, such as hydrogen cyanide.

From the "gap problems" described above it can be inferred that the application of a safety wall with its gap is not to be recommended in many cases. The form of construction C--SIS will, however, inevitable have to be employed if an existing tank afterwards has to be
provided with a second containment structure ("line of defence") in the form of a safety wall. In such a case the designer should pay considerable attention to the connection of the bottom of the tank to the concrete structure subsequently to be built.

In connection with the construction of a safety wall around an existing tank it is necessary to take precautions against damage to the tank due to the constructional operations. The gap should be sufficiently wide also from this point of view.

Summary C--SIS

Functions of the concrete wall (C)

<table>
<thead>
<tr>
<th>Loadbearing</th>
<th>Containment</th>
<th>Insulation</th>
<th>Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>liquid in the</td>
<td>liquid in the</td>
<td>(not applicable)</td>
<td>primary</td>
</tr>
<tr>
<td>event of disaster</td>
<td>event of disaster</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Construction

- base: not necessarily of concrete
- wall: prestressed concrete
- roof: on steel tank
- foundation: wall may be founded separately from tank
- arrangements for wall: none
- arrangements for earth banking: safety wall may be concrete enclosing wall of catch basin

- temperature of stored liquid: no restriction
- special problems: gap problems - annular space often also liquid-tight connection wall-base-tank, especially for subsequently installed safety walls
Gas-terminal Enagas-Barcelona
LNG tank under construction
Information page 139
Fig. 23. Single-walled steel tank, insulated on the outside and surrounded by a concrete safety wall (C—IS)

Note: Other solutions are also possible for the structural details such as wall-to-base and wall-to-roof connections.
4.4 Single-walled steel tank, insulated on the outside and surrounded by a concrete safety wall (C-IS) (fig. 23)

This form of construction has much in common with the C-SIS system (see 4.3). The single-walled storage tank, built of steel suitable for the purpose, is provided with an insulating layer on the outside. This insulation is generally sheathed with a thin "skin" of ordinary (carbon) steel or of aluminium (IS, see 4.2).

In principle, the tank supports the roof structure, so that the insulating layer is in an open cavity. Hence the above-mentioned "skin" should be watertight. This form of construction is appropriate for the storage of liquefied cooled gases with not too low a boiling point (e.g., not below -50 °C: see 3.10.3). The insulating layer is, as a rule, thinner than that used in the C-SIS system (see 4.3) and its insulating effect is accordingly less than in that system. In view of the similarity with C-SIS, the advantages and disadvantages already enumerated for that system are applicable also to C-IS. The "gap problems" deserve particular attention in this case.
Summary C--IS

Functions of the concrete wall (C)

<table>
<thead>
<tr>
<th>Loadbearing</th>
<th>Containment</th>
<th>Insulation</th>
<th>Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>liquid in the event of disaster</td>
<td>liquid in the event of disaster</td>
<td>(not applicable)</td>
<td>primary</td>
</tr>
</tbody>
</table>

Construction

| base | not necessarily of concrete |
| wall | prestressed concrete |
| roof | on steel tank |
| foundation | wall may be founded separately from tank |
| arrangements for wall | none |
| arrangements for earth banking | safety wall may be concrete enclosing wall of catch basin |
| temperature of stored liquid | in connection with IS, temperature generally not to be below about -50 °C |
| special problems | gap problems - annular space often also liquid-tight connection wall-base-tank, especially for subsequently installed safety walls |
Peak-shaving plant - Maasvlakte - Nederlandse Gasunie - Rotterdam Europort
Slip forming of concrete safety wall
Information page 232
Design: Protech International
Fig. 24. Single-walled steel tank, surrounded by a concrete safety wall which is insulated on the inside (C1--S)

Note: Other solutions are also possible for the structural details such as wall-to-base and wall-to-roof connections

1 = carbon steel
2 = steel roof structure
3 = chrome-nickel steel (or aluminium)
4 = concrete structure
5 = perlite (or similar granular insulating material) \( I_p \)
6 = foamed glass (or similar loadbearing insulating material) \( T_b \)
7 = glass wool blanket (or a similar material) \( I_w \)
8 = perlite concrete (or a similar material)
9 = balsa wood (or a similar material)
10 = rigid insulating material \( T_p \)
11 = aluminium
12 = vapour-tight layer
13 = liner (carbon steel)
14 = vapour-tight and liquid-tight membrane (chrome-nickel steel or stainless steel)
15 = heating pipe
16 = joint structure
17 = seal
18 = pile (or column)
19 = water discharge
20 = rubber bearing
4.5 Single-walled steel tank, surrounded by a concrete safety wall which is insulated on the inside (CI--S) (fig. 24)

This form of construction has the advantages offered by a concrete safety wall, as in the systems C--SIS (see 4.3) and C--IS (see 4.4), but there are fewer "gap problems", since the safety wall supports the roof structure, so that the gap is covered. Like the insulation cavity in double-walled steel tanks, the gap will in many cases be almost always filled with gas because it is in open communication with the gas-filled space within the inner tank. The risk of a combustible or explosive gas/air mixture is ruled out in this case. Inspection of the outside of the primary tank is no simple matter, however, and is possible only at times when the installation is not in use and the storage tank is empty.

In this form of construction the safety wall functions as the outer tank of a double-walled tank. Usually constructed of prestressed concrete, the safety wall is provided with an insulating layer covering its entire internal surface and bonded to the concrete. This layer must not be attacked by the gas that is present in the gap. An advantage offered by the insulating layer is that it prevents the concrete wall being exposed to "temperature shock" in the event of leakage or failure of the inner tank. Also, there will not be such intense evaporation when the liquid comes into contact with the safety wall.

As in the C--IS system (see 4.4), the insulating layer is, as a rule, thinner than in the C--SIS system (see 4.3), so that its insulating effect is less. Hence this form of construction is suitable only for the storage of liquefied cooled gases with not too low a boiling point (e.g., not below about -50 °C).

Since a concrete wall is not completely vapour-tight, it is necessary to make arrangements to prevent the penetration of moisture from outside. Such moisture could give rise to the undesirable formation of ice lenses between the insulation and the concrete if these are not
entirely bonded together over the whole surface and the temperature is locally below 0 °C. This may occur in the case of a steel liner applied to the internal surface of the outer tank. The liner may then become locally detached from the concrete if, during the filling of the tank ("cooldown"), large differences in temperature develop between the cold steel plate and the still warm concrete wall.

For this reason it is better to incorporate a steel liner in the concrete, preferably as close to the outside as possible. There will then be practically no temperature differences, and the temperature will not fall below zero at the liner. The latter can, in that case, be made of ordinary carbon steel.

With certain construction methods and prestressing systems, more particularly the so-called wrapping or winding method, this is an obvious solution to choose, because the steel liner will then be under compressive stress (prestress). The concrete wall employed in this form of construction has the advantage that now the roof structure can also be of concrete. A concrete roof is well able to withstand gas overpressure and underpressure, which is favourable from the plant operating point of view. As regards the safety against internal influences, a roof of this kind also offers many possibilities, in which case it should of course be designed for this loading.
Summary CI--S

Functions of the concrete wall (C)

<table>
<thead>
<tr>
<th>Loadbearing</th>
<th>Containment</th>
<th>Insulation</th>
<th>Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>gas pressure</td>
<td>gas</td>
<td>gas temperature</td>
<td>in the event of disaster</td>
</tr>
<tr>
<td>liquid in the</td>
<td>liquid in the</td>
<td></td>
<td></td>
</tr>
<tr>
<td>event of disaster</td>
<td>event of disaster</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Construction

- base: concrete
- wall: prestressed concrete
- roof: steel or concrete, depending on safety requirements
- foundation: wall may be founded separately from tank
- arrangements for wall: gas-tight coating on inside
- insulation on inside
- possibly: vapour-tight coating on outside
- arrangements for earth banking: concrete wall may be enclosing wall of catch basin
- temperature of stored liquid: in general not lower than about \(-50\) °C
- (in connection with thickness of insulation)
- special problems: gas-tight and liquid-tight connection wall-base
- with direct earth banking, the banked earth may freeze; hence heating is needed there
- this applies also to the soil under the base (even if there is no earth bank)
Fig. 25. Double-walled tank, with steel inner tank and concrete outer tank, and insulation between them (CIS)

Note: Other solutions are also possible for the structural details such as wall-to-base and wall-to-roof connections.

1 = carbon steel
2 = steel roof structure
3 = chrome-nickel steel (or aluminium)
4 = concrete structure
5 = perlite (or similar granular insulating material) $I_g$
6 = foamed glass (or similar loadbearing insulating material) $I_b$
7 = glass wool blanket (or a similar material) $I_c$
8 = perlite concrete (or a similar material)
9 = balsa wood (or a similar material)
10 = rigid insulating material $I_b$
11 = aluminium
12 = vapour-tight layer
13 = liner (carbon steel)
14 = vapour-tight and liquid-tight membrane (chrome-nickel steel or stainless steel)
15 = heating pipe
16 = joint structure
17 = seal
18 = pile (or column)
19 = water discharge
20 = rubber bearing
Double-walled tank, with steel inner tank and concrete outer tank, and insulation between them (CIS) (fig. 25)

This form of construction resembles the double-walled steel tank SIS (see 4.2) in many respects, except that now the outer tank is of prestressed concrete. Because of this, the system in fact has the advantages of a concrete safety wall, as in the C--SIS (see 4.3), C--IS (see 4.4) and CI--S (see 4.5) systems, but without the drawbacks associated with the annular space (gap).

Just as in the double-walled steel tank, the insulation cavity between the inner and the outer tank will usually be filled with gas. But this is not an objectionable feature here either, since the insulation will function quite effectively even when gas is present. It is, however, necessary to make arrangements, as in the CI--S system (see 4.5), to prevent the penetration of moisture and, possibly, the escape of gas. The same solution as in that system can suitably be employed, i.e., a vapour-tight layer or a steel liner incorporated in the concrete wall. The insulating value of the cavity filled with insulating material (e.g., perlite) between the inner and the outer tank can be much greater than that of the insulating layer used in the C--IS (see 4.4) and CI--S (see 4.5) systems. Hence this form of construction may also be suitable for use with storage temperatures lower than about -50 °C.

Just as in the CI--S system, with this form of construction a concrete roof can be provided, which is favourable both from the plant operating and from the safety point of view (see 4.5). A disadvantage of this solution is, however, that if the inner tank loses its contents due to leakage or failure, the cold liquid will - on passing through the perlite filling - come into direct contact with the warm concrete wall. The resulting evaporation, with evolution of gas, may be so intense as to cause a considerable rise in the internal pressure in the tank. If this possibility has not been taken into account in that, for example, an insulating layer attached to the concrete wall and able to withstand low temperatures has been omitted, such omission will constitute a direct hazard to the wall and roof.
The CIS form of construction presents some of the features of a so-called "integrated tank" (see 2.2.3), since the outer tank can, if necessary, perform the task of the inner tank and can moreover function as a safety wall.
Summary CIS

Functions of the concrete wall (C)

<table>
<thead>
<tr>
<th>Loadbearing</th>
<th>Containment</th>
<th>Insulation</th>
<th>Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>gas pressure</td>
<td>gas</td>
<td>gas temperature</td>
<td>in the event of disaster</td>
</tr>
<tr>
<td>liquid in the event of disaster</td>
<td>liquid in the event of disaster</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Construction**

- **base**: reinforced concrete possibly: prestressed concrete
- **wall**: prestressed concrete
- **roof**: preferably concrete (possibly: steel, depending on safety requirements)
- **foundation**: combined foundation for tank as a whole base free from subsoil, if possible
- **arrangements for wall**: gas-tight coating on inside\(^*\) insulating layer firmly attached to wall possibly: vapour-tight coating on outside\(^*\)
- **arrangements for earth banking**: preferably separate catch basin in which this CIS is installed
- **temperature of stored liquid**: usually very low temperature (e.g., -160 °C)
- **special problems**: if base rests on subsoil, local heating is required wall-base connection preferably jointless

\(^*\) steel liner in concrete wall can perform both functions
Fig. 26. Double-walled concrete tank, with insulation between inner and outer tank (C_LIC_L)

Note: Other solutions are also possible for the structural details such as wall-to-base and wall-to-roof connections.

1 = carbon steel
2 = steel roof structure
3 = chrome-nickel steel (or aluminium)
4 = concrete structure
5 = perlite (or similar granular insulating material) T_p
6 = foamed glass (or similar loadbearing insulating material) T_b
7 = glass wool blanket (or a similar material) T_c
8 = perlite concrete (or a similar material)
9 = balsa wood (or a similar material)
10 = rigid insulating material T_b
11 = aluminium
12 = vapour-tight layer
13 = liner (carbon steel)
14 = vapour-tight and liquid-tight membrane (chrome-nickel steel or stainless steel)
15 = heating pipe
16 = joint structure
17 = seal
18 = pile (or column)
19 = water discharge
20 = rubber bearing
4.7 **Double-walled concrete tank, with insulation between inner and outer tank \( C^IC^L \) (fig. 26)**

This form of construction is very similar to the CIS system (see 4.6), though now the inner tank is also of prestressed concrete. Structurally the inner and the outer tank are equivalent. This means that the outer tank can, if necessary, perform the duty of the inner tank and moreover functions as a safety wall. The system therefore clearly constitutes a so-called "integrated tank" with a high degree of safety.

Just as in the CIS (see 4.6) and CI--S (see 4.5) systems, the concrete outer tank must be of vapour-tight construction. The solutions suitable for the purpose are also the same as those already described, i.e., a liner installed in the concrete or a vapour-tight layer between the insulation and the concrete. The concrete inner tank should, first and foremost, be liquid-tight and, in special cases, also vapour-tight. A steel liner installed in the concrete is more particularly suitable for the purpose.

A double-walled concrete tank provides good possibilities of also constructing the roof in concrete, should this be considered necessary - either on the inner or on the outer tank (see 4.5). Since the hazard of large quantities of liquid suddenly pouring out of the inner tank can be ruled out in this case, there is no risk of a sudden considerable increase in gas pressure in the tank in consequence of intense evaporation of liquid.
Summary \( C_{LIC}\)

Functions of the concrete wall \((A: C_L; B: C_L)\)

<table>
<thead>
<tr>
<th>Loadbearing</th>
<th>Containment</th>
<th>Insulation</th>
<th>Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>A gas pressure liquid in the</td>
<td>gas liquid in the event of disaster</td>
<td>none</td>
<td>primary</td>
</tr>
<tr>
<td>B liquid pressure liquid and gas</td>
<td>none</td>
<td></td>
<td>(not applicable)</td>
</tr>
</tbody>
</table>

**Construction**

- **base**: reinforced concrete; possibly: prestressed concrete
- **wall**: A and B prestressed concrete
- **roof**: on A, preferably concrete; alternatively, sometimes on B if safety requirements are very strict: then A and B of concrete
- **foundation**: combined foundation for tank as a whole; base free from subsoil, if possible
- **arrangements for wall**: A and B: steel liner in wall
- **arrangements for earth banking**: wall A may be the wall of the catch basin; heating!
- **temperature of stored liquid**: usually very low temperature (e.g., \(-160^\circ C\))
- **special problems**: a joint structure is necessary between wall B and base; connection of wall A to base may be jointless

Note: The steel liner in wall A may be replaced by arrangements as indicated for CIS (fig. 25).
Safety wall - Ammonia tank
Nederlandse Stikstof maatschappij - Sluiskil (Netherlands)
Design and Construction, B.V. Nederlandse Bouw Maatschappij N.B.M.
System C--IS
Diameter tank wall 50 m
Height of prestressed concrete wall 28 m
Foundation on 72 piles, concreted in situ, diameter Ø 130 cm, length 32.5 m
Fig. 27. Single-walled concrete tank, insulated on the outside (SIC\textsubscript{L})

Note: Other solutions are also possible for the structural details such as wall-to-base and wall-to-roof connections

1. carbon steel  
2. steel roof structure  
3. chrome-nickel steel (or aluminium)  
4. concrete structure  
5. perlite (or similar granular insulating material) \( I_f \)  
6. foamed glass (or similar loadbearing insulating material) \( I_b \)  
7. glass wool blanket (or a similar material) \( I_c \)  
8. perlite concrete (or a similar material)  
9. balsa wood (or a similar material)  
10. rigid insulating material \( I_b \)  
11. aluminium  
12. vapour-tight layer  
13. liner (carbon steel)  
14. vapour-tight and liquid-tight membrane (chrome-nickel steel or stainless steel)  
15. heating pipe  
16. joint structure  
17. seal  
18. pile (or column)  
19. water discharge  
20. rubber bearing
4.8 Single-walled concrete tank, insulated on the outside (SIC₈) (fig. 27)

In the double-walled concrete tank C₂IC₈ (see 4.7) the inner and the outer tank, both of prestressed concrete, are structurally equivalent. Hence the outer tank is able to perform the duty of the inner tank. It is very unlikely that it will ever have to do this, however, as the inner tank cannot fail so long as there are no external influences to harm it. (The outer tank, after all, functions also as a safety wall!).

If no outer tank, as envisaged here in SIC₈, is provided, the insulation applied to the exterior of the storage tank will have to be enclosed to prevent the ingress of moisture. A sheathing of ordinary (carbon) steel plate or possibly of aluminium can be used for the purpose.

For vapour-tightness and liquid-tightness, the concrete wall is provided with a liner which, just as in the C₂IC₈ system (see 4.7), should be installed in the concrete, at any rate if a steel liner is employed. This form of construction, which displays some of the features of a so-called "integrated tank" (see 2.2.3), may likewise be given a roof structure built of concrete, which is advantageous both with regard to safety and with regard to plant operation (see 4.5).
### Functions of the concrete wall (C)

<table>
<thead>
<tr>
<th>Loadbearing</th>
<th>Containment</th>
<th>Insulation</th>
<th>Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>liquid</td>
<td>liquid and gas</td>
<td>none</td>
<td>in the event of disaster</td>
</tr>
</tbody>
</table>

### Construction

- **base**: reinforced concrete possibly: prestressed concrete
- **wall**: prestressed concrete
- **roof**: steel or concrete, depending on safety requirements
- **foundation**: combined foundation for tank as a whole base free from subsoil, if possible
- **arrangements for wall**: steel liner in the wall
- **arrangements for earth banking**: banking with earth is possible only if there is a separate concrete catch basin
- **temperature of stored liquid**: suitable for a wide range of temperature
- **special problems**: this solution is possible only if no special loads of external origin are liable to occur a joint has to be provided between wall and base
Gas-terminal Enagas Barcelona
Connection Concrete Roof with outer wall
Steel roof used as a mould for the concrete structure of the dome
Fig. 28. Single-walled concrete tank, insulated on the inside (CIL)

Note: Other solutions are also possible for the structural details such as wall-to-base and wall-to-roof connections.

1 • carbon steel
2 • steel roof structure
3 • chrome-nickel steel (or aluminium)
4 • concrete structure
5 • perlite (or similar granular insulating material) \( \text{I}_p \)
6 • foamed glass (or similar loadbearing insulating material) \( \text{I}_b \)
7 • glass wool blanket (or a similar material) \( \text{I}_c \)
8 • perlite concrete (or a similar material)
9 • balsa wood (or a similar material)
10 • rigid insulating material \( \text{I}_b \)
11 • aluminium
12 • vapour-tight and liquid-tight membrane (chrome-nickel steel or stainless steel)
13 • liner (carbon steel)
14 • vapour-tight and liquid-tight membrane (chrome-nickel steel or stainless steel)
15 • heating pipe
16 • joint structure
17 • seal
18 • pile (or column)
19 • water discharge
20 • rubber bearing
4.9 Single-walled concrete tank, insulated on the inside (CIL) (fig. 28)

This form of construction has the advantages of the SIC₇ system (see 4.8), but not its disadvantages (low level of safety against external influences), because now the concrete tank is insulated on the inside. The tank performs the functions of resisting the forces arising from the storage of liquid and of providing protection against internal and external influences. By virtue of this integration of functions this is the most obvious example of a so-called "integrated tank". Since the insulation must be able to transmit the liquid pressure to the structural wall of the tank, the inner face of this insulation (i.e., the interface between the insulation and the liquid) can adequately consist of a membrane which, while having to be liquid-tight and vapour-tight, is not subjected to any loading. (A vapour-tight layer is usually installed between the insulation and the concrete, unless the insulation itself performs this function). If the insulation also serves as a vapour barrier, it must be intimately attached to the concrete over the entire contact surface area. The insulating layer should then be so composed that it can resist or absorb temperature stresses without serious detriment to its vapour-tightness and insulating value. Good materials are available for such a "loadbearing insulation" (see 3.10.3).

The membrane may consist of stainless steel, chrome-nickel steel or Invar sheets which have to be assembled in situ by welding. It has no structural function to perform, i.e., it does not have to transmit any loading, and may therefore be fairly thin and flexible. The main requirements to be fulfilled by the membrane are liquid-tightness and vapour-tightness. On completion of the welding operations, the membrane should therefore be carefully checked and tested for these properties. A constant check on the proper functioning of the membrane is possible by the introduction of nitrogen between it and the insulation.

There are liquid-retaining insulating materials which possess a fairly high degree of liquid-tightness and vapour-tightness. Such
materials offer an extra margin of safety in the event that the membrane is damaged (from whatever cause), because they prevent the cold liquid from coming into direct contact with the "warm" concrete wall (see 6.5). As already explained, this can cause intense evaporation of the liquid attended by uncontrolled increase in gas pressure in the tank (wall-roof).

Membranes have been developed which derive their flexibility and their capacity for undergoing temperature variations without axial deformations from their special shape characterized by arch-like curved features in two directions. This type of membrane is 2 - 4 mm thick. The small "arches" have to transmit the pressure exerted by the liquid to the contact surfaces with the loadbearing insulation behind the membrane.

Membranes made of Invar may be installed virtually taut, as they undergo very little axial deformation under the influence of temperature variations. For this reason a thickness of about 1 mm is sufficient, and this low thickness makes for great flexibility of such membranes.

The various types of membrane have been developed industrially and therefore form part of a complete system in which design, materials and execution of the work are closely interadjusted.

This insulation applied to the inside of the concrete tank also ensures that the "temperature shock" to the concrete wall (occurring when the tank is being filled, for example) is duly limited, since this wall hardly comes into contact with the cold liquid.

Finally, this type of insulation has the advantage that the concrete wall is subjected only to temperature variations of limited magnitude. Hence no complicated joint constructions between the wall and the base are required, such as can hardly be dispensed with in the other forms of construction. In this system a concrete roof with all its advantages is an obvious choice (see 4.5).
It is to be noted that this structural solution has also been used for the construction of concrete ships for the transport of liquefied cooled gases such as LNG [5-3].
Summary CIL

Functions of the concrete wall (C)

<table>
<thead>
<tr>
<th>Loadbearing</th>
<th>Containment</th>
<th>Insulation</th>
<th>Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>liquid and gas</td>
<td>gas</td>
<td>liquid</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>liquid in the event of disaster</td>
<td>temperature</td>
<td>in the event of disaster</td>
</tr>
</tbody>
</table>

Construction

| base         | prestressed concrete possibly: reinforced concrete |
| wall         | prestressed concrete |
| roof         | preferably of concrete construction |
| foundation   | combined foundation for tank as a whole base of tank free from subsoil, if possible |
| arrangements for wall | gas-tight and liquid-tight coating on inside liquid-tight insulation firmly attached to concrete wall possibly: vapour-tight coating on outside |
| arrangements for earth banking | preferably in a separate catch basin |
| temperature of stored liquid | usually very low temperature (e.g., -160 °C) |
| special problems | wall-base connection jointless |

* steel liner in concrete wall can perform both functions
Gas-terminal Enagas Barcelona
Design and Construction Auxini-Preload
System $C_L IC_L$
Horizontal prestressing with "merry go round" system
Capacity tank 80,000 m$^3$
Diameter outer tank 85.5 m
Prestressed concrete walls thickness 0.35 m
Fig. 29. Single-walled concrete tank, insulated on the inside, and surrounded by a concrete safety wall (C–CIL)

Note: Other solutions are also possible for the structural details such as wall-to-base and wall-to-roof connections
4.10 Single-walled concrete tank, insulated on the inside, and surrounded by a concrete safety wall (C--CIL) (fig. 29)

The CIL form of construction (see 4.9) offers a substantial number of advantages. The wall can be designed to such dimensions that it will adequately withstand external influences (e.g., flying fragments hurled away from an explosion, sabotage activities). However, after having been subjected to such influences, the wall will often have suffered more or less serious damage. This means that the safety of the storage conditions will temporarily be much reduced. An obvious means of obtaining protection against external influences is by providing a separate concrete safety wall which may indeed suffer damage without detriment to the safety of the actual storage tank: C--CIL. Actually, this safety wall is a "tertiary" wall.

In that case the safety wall has the sole duty to protect the storage tank against external influences, not to act as an emergency liquid-retaining structure ("second line of defence"). Thus, this safety wall may be provided with openings for the discharge of water that has entered and for ventilation in order to get rid of any gas that has got into the gap. Besides, a fairly wide gap may be used, since there are no reasons why it should be kept as narrow as possible.

For these reasons this form of construction does not have to contend with the "gap problems" which are liable to arise in connection with other applications of a safety wall (see 4.3). In this case the safety wall need not be designed for a "liquid impulse", a "temperature shock", etc. It can therefore be built of reinforced concrete. This is, in fact, the only instance where reinforced concrete can suitably be used for wall structures for "unpressurized cooled storage" which are entirely above ground level (see 3.9). It is furthermore important that this safety wall can be founded quite independently of the actual storage tank.

Also, the safety wall can function as an earth-retaining (and groundwater-retaining) structure if it is decided to bank the catch basin with earth.
Summary C--CIL

Note: for CIL wall see CIL

<table>
<thead>
<tr>
<th>Functions of the concrete wall (A: C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loadbearing</td>
</tr>
<tr>
<td>none</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>base</td>
</tr>
<tr>
<td>wall</td>
</tr>
<tr>
<td>roof</td>
</tr>
<tr>
<td>foundation</td>
</tr>
<tr>
<td>arrangements for wall</td>
</tr>
<tr>
<td>arrangements for earth banking</td>
</tr>
<tr>
<td>temperature of stored liquid</td>
</tr>
<tr>
<td>special problems</td>
</tr>
</tbody>
</table>
Underground and/or earth-banked storage tanks

The forms of construction described in this chapter have so far comprised above-ground storage tanks. Most of them, however, can suitably be installed in a "pit" formed in the ground, the tank being so placed as to stand free from the sides of this "pit". This arrangement is necessary because direct burial of a tank in the ground, or the banking of earth against its wall, i.e., so that the tank is in direct contact with the soil, presents some specific problems which will be dealt with in general terms in this section.

Earth-banked tank

An above-ground storage tank may, if its external wall is of concrete, be partly provided with a backfill of earth which rests against the tank and forms a slope or bank over the full height of the tank or over part of the height. This earth bank gives improved protection against all kinds of external and also against some internal influences.

Fig. 30. Earth-banked concrete tank
The earth backfill will, however, cause settlement in the subsoil. As a result of such settlement, the magnitude of which will depend on the nature of the subsoil, frictional forces will be exerted on the wall of the tank, i.e., the latter will be subject to additional vertical loading (fig. 30). This "negative skin friction" can be reduced by providing the wall with a special sliding layer. Settlement phenomena give rise to problems more particularly in connection with tanks on piled foundations in very soft ground. In such cases, extra arrangements around the piled foundation will be required, e.g., a diaphragm wall (fig. 30).

Banking the concrete outer tank with earth backfill is relatively simple in all cases where there is a gap between the inner tank and the outer wall. If there is no gap, the thermal problems encountered will be more serious (see below).

**Underground tanks**

A storage tank can be installed wholly or partly under ground, or to be more precise: below ground level, i.e., let into the ground, an arrangement which hitherto has been adopted chiefly in Japan. A tank buried in this way is of course well protected against external influences: primarily earthquakes, but also the effects of a nearby fire or explosion, flying fragments, sabotage activities, etc. Besides, such a tank will look less unsightly in the landscape than an above-ground tank. Because of the lower elevation above ground level, the consequences of "undesirable events", followed more particularly by the contents of the tank catching fire and by the formation of a cloud of gas, are liable to be more serious than with an above-ground tank, however. Furthermore, the roof is "more vulnerable", so that its design will require extra attentions. For this reason, too, the tank roof may be covered with a layer of soil. In the Netherlands this is, in general, not a practicable form of construction.

The following problems may further arise in connection with a wholly or partly buried tank (here referred to as an "underground" tank):
1. If the tank wall and tank base are kept separate from each other, they will separately transmit their loads to the subsoil. As a result, at the foot of the wall, the horizontal and vertical soil stresses on the outside may become much larger than those on the inside. In consequence of this, surfaces of sliding (shearing surfaces) may develop in the ground. This problem can be overcome, inter alia, by extending the tank wall a long way below the base (fig. 31).

![Fig. 31. Separate foundation of tank wall and tank base](image)

2. If the tank wall and the tank base are "monolithically" joined together, settlement of the wall and backfill may impose an additional load, acting upwards, upon the base (fig. 32). This "counter-pressure" is more particularly due to the fact that the base, too, has a major share in transmitting the loads exerted by the tank wall to the subsoil.
In many cases, as more particularly in the Netherlands, the base of the tank will have to be installed below the (highest) groundwater level. This may present various problems:

3.1. Horizontal (water) pressure on the tank wall:
The horizontal pressure caused by the groundwater will give rise to "compressive ring forces" in the tank wall. If the wall deviates locally from the circular shape, those compressive forces will be acting eccentrically upon the wall section there. As a result, the stability of the wall with regard to "implosion" may be adversely affected due to this "out of roundness".

3.2. Uplift (vertical) force on the tank structure:
The groundwater causes an upward force (fig. 33) ("buoyancy") which can be counteracted by giving the tank a considerable dead weight. In the case of high tanks which are wholly or partly submerged in the groundwater this solution will necessitate the construction of a particularly heavy base slab. An alternative solution may sometimes be available by installing vertical ground anchors in the subsoil which are able to develop tensile forces to resist the uplift.
Fig. 33. Forces upon tank wall and tank base by the groundwater

4. The presence of groundwater around the tank makes special demands upon the watertightness of the tank wall.

5. In the case of wholly or partly buried tanks it is necessary to ensure that the surrounding soil will not freeze up. This require-
ment more particularly presents a problem in connection with the storage of LNG and other liquefied gases with a very low storage temperature. Freezing of the groundwater beside the tank wall and under the base will be associated with an increase in volume which can generate quite considerable forces, so that the whole tank structure may be lifted. This lifting effect ("frost heaving") is generally greater than is directly deducible from the water involved. This is so because freezing lowers the vapour pressure, with the result that water and water vapour are attracted from the surroundings and, in due course, freeze to ice. It would seem that this process can continue for a very long time. It should be possible to overcome the problem of "frost heaving" by heating the subsoil. To this end, a heating system is installed on the outside of the concrete structure (wall and base). This system, which should be of sufficient capacity to keep the temperature of the surrounding soil above the freezing point of water, will have to remain functional throughout the service life of the tank and will continuously consume energy. The effect of the heat input is difficult to verify, as visual inspection of the outside of the tank wall and base is not possible. Besides, renewal of heating cables or wires, should that become necessary, is a difficult and/or expensive operation.

Another arrangement, which may be applied in combination with a heating system, consists in pumping the groundwater out of the surrounding soil. No ice formation can occur in the soil thus constantly drained. However, this solution suffers from many of the same drawbacks as those associated with soil heating (energy consumption, difficulty of inspection, difficult and/or expensive repairs, etc.). Also, for efficient drainage by pumping, the tank structure will often have to be installed in soil possessing a high degree of permeability to water (e.g., coarse sand).

6. When an underground tank is cooled down for the first time, the surrounding soil is liable to "settle", because the diameter of the tank decreases due to thermal contraction on cooling. When the tank is subsequently emptied, which is associated with a rise in temperature of the tank wall, the expansion of the latter will be opposed by the soil that has consolidated around the tank when it was cold. Under such
circumstances, too, local deviations from true circularity of the tank wall may have an unfavourable effect.

In principle, any type of tank provided with a concrete outer tank can be built as an underground tank, provided that the above-mentioned problems are duly taken into consideration. This means that the following forms of construction can be used: CIC, CIC, and CIL. The solutions embodying a gap are discussed below. With regard to the CICL types of tank it is to be noted that, in the above-ground version, a plain (unreinforced) "concrete wall" is interposed between the tank wall and the insulation and is intended more particularly as a protection against external influences. In the case of tanks buried in the ground this "concrete wall" is not necessary. The outer concrete wall is usually constructed of prestressed concrete. In some instances reinforced concrete has been used. With underground tanks it will often be the pattern of forces that can be expected to occur (also under exceptional conditions) that justifies a particular solution, in prestressed or in reinforced concrete.

4.12 Tank standing free in a separate pit

The problems described above will be largely obviated if the tank is surrounded by an annular gap which should moreover extend under the base of the tank, this being achieved by mounting the tank on columns in the pit. With this solution the actual storage tank stands, as it were, as a completely independent structures in a "pit". The wall of the pit may, for example, be half above ground, and the upper part of this wall may be banked with earth (fig. 34). The gap can of course give rise to one or more of the "gap problems" already referred to (see 4.3). The tank pit may be constructed of concrete cast in situ or it may be concerned off the site and floated into position.

The shape and dimensions of the pit will vary according to the type of tank that will be installed in it. In all cases where the tank pit also has to constitute a containment structure, i.e., a catch basin to receive the contents that may flow out of the storage tank in an emergency, the concrete structure of the pit must also be designed
to withstand the loads, impacts, temperature effects, etc. that are liable to occur under such conditions.

Fig. 34. Tank standing free in a separate pit

More particularly this therefore applies to the following forms of construction:

C—SIS in which the safety wall is the tank pit (see fig. 22);
C—IS in which the safety wall is the tank pit (see fig. 23);
CI—S in which the safety wall is the tank pit (see fig. 24);

In this case there is, however, the problem that under service conditions a temperature gradient will develop through the insulation, concrete wall and soil and that, in the event
of failure of the inner tank, this gradient will become very considerable (freezing of the soil). If the stored liquid has a low boiling point, the soil temperature is liable to fall below 0 °C, in which case it will be necessary to apply heating to this soil.

C--CIL in which the safety wall is the wall of the tank pit (see fig. 29).

In the forms of construction CIS (see fig. 25) and SIC, (see fig. 27) a separate pit will be an obvious choice, at any rate if the problems associated with completely earth-banked tanks, as mentioned in 4.11, are to be avoided. This tank pit then forms what is virtually a tertiary wall. Such a wall will therefore not have to be designed to withstand the consequences of an outflow of liquid from the inner tank and it can therefore suitably be built of reinforced concrete. In this case the earth banking around the pit or catch basin will play a major part in protecting the storage tank against extreme influences.

4.13 Concrete roof structure

A roof structure built of concrete can be mounted directly on a concrete wall of tank. The wall should of course be designed to carry the loads transmitted to it from the roof. A concrete roof structure is often designed as a shell roof whose prestressed concrete edge beam resists the outward thrust forces. The dimensions of the roof structure will depend on the loads to which it will be subjected.

For the sake of gas-tightness the inside of the concrete roof is often provided with a steel liner, which, strengthened by a supplementary steel structure, also often serves as (permanent) formwork for the concrete roof.

If the concrete roof structure has to be insulated on the inside, the requisite insulating materials will be in the form of "coherent" elements (blankets, blocks, etc.).

The roof structure should be designed to withstand possible overpressure and underpressure in the tank. The internal overpressure is
compensated - but usually in part only - by the dead weight of the roof. In the case of fairly large overpressure the roof structure, functioning as a membrane, will have to transmit the forces to the concrete wall. In order to obviate cracking of the concrete under these loading conditions, it will be necessary to prestress it. With regard to the mounting of installations on the concrete roof it must be pointed out that the roof will - under the influence of temperature changes occurring in it - undergo a vertical deformation which will be largest at mid-span. In general, a concrete roof will be an obvious choice in cases where pipelines are located on the roof of the tank. Leakage of these pipelines or their valves can never be completely ruled out, in which case cold liquid may run out onto the roof. A concrete roof will not suffer any ill effects from this. If the roof is to be covered with earth, it will have to be designed to substantially stouter dimensions, certainly if large roof spans are involved.

4.14 The optimum design

In the foregoing sections a number of forms of construction for tanks have been described and critically assessed, thus establishing a basis for arriving at an optimum design for the storage of certain substances in actual practice. By "optimum" is more particularly to be understood a design which fulfils all the applicable requirements with regard to:

- safety: safeguards and precautions especially also with reference to the protection of human life, to the materials involved and to the type of installation for which the storage tanks are required (peak shaving, intermediate storage, etc.);
- piping system;
- spacing of tanks and installations (including the cost of land and other such considerations);
- cost of the actual tank structure;
- consequences, in the financial sense, of a disaster (insurance premium);
- aesthetics - aspect of the structures in the landscape.
Obviously, the functions enumerated here will represent different values from one case to another. In connection with these considerations it will of course be necessary also to carry out a risk analysis in order to be able to evaluate different solutions in relation to one another in this respect as well.

Since the solutions to be chosen will be strongly influenced by the above-mentioned cost evaluation, partly also with regard to the type of storage envisaged, it is not possible to make comparisons between the various construction systems. That would be outside the scope of this report.

To finalize this chapter information can be given about a paper on the subject which had, incidentally, been published already in md-1977 [6-21]. In that paper, nine solutions for tanks intended for the storage of liquefied natural gas are evaluated according to a method first proposed by Dr. Fr. Kesselring in 1954. Some interesting conclusions drawn in this paper, will be given here.

This evaluation of the solutions adopted for tanks relates to the following subjects, among others:

1. Safety

1.1. Primary safety, comprising:

- safety of the foundation
- risk of freezing of the subsoil
- the structure of the outer tank wall
- the structure of the inner tank wall
- the covering of the actual liquid-containing vessel
- quality of the insulation
- safety against special external loads
- safety of the inner wall against special loads
- safety against events of internal origin

1.2. Secondary safety, comprising:

- problems associated with a tank pit (gap)
- sprinkler system
- safety of outer wall against forces of internal origin
safety in the event of formation of gas clouds
safety in the event of fire (installation or tank itself)
firefighting possibilities
possibility of pumping out the LNG in a disaster

2. Other technical aspects, such as:
problems of construction
corrosion protection of the outer wall
groundwater problems
errection problems; possibility of dismantling

3. Environment

noise nuisance during construction, etc.
the tank structure in the landscape

4. Evaluation of subcontractor with regard to experience in the execution of work of this kind

5. Economic evaluation

Since it is important to know the results of this evaluation in order to assess the value of the present report, some of the conclusions based on the above-mentioned paper will be given here. These relate to the evaluation of safety (1.1. and 1.2.).

For this purpose a minimum rating of 220 and a maximum rating of 400 points is indicated.

With respect to 1.1. and 1.2. the SIS system is rated at 228 points, the C--SIS system at 284 points and the CIS system at 338 points.

The differences in rating between the systems are due mainly to differences in evaluation of the following subjects:

- safety of inner and outer tank wall against external loads
- safety of the tank pit
- safety against forces of internal origin
- safety in the event of formation of a gas cloud or outbreak of fire, as well as the possibilities of firefighting and pumping out the LNG.
LOADS TO BE ADOPTED IN THE DESIGN CALCULATIONS

This chapter will deal more particularly with the "design loads" for concrete structures intended for "unpressurized cooled storage".

First, the design criteria (see 5.1) will be considered, and then the ordinary loads when the storage structure is in normal use (see 5.2), as well as the special loads due to undesirable events of internal origin (see 5.3) and of external origin (see 5.4). After a review of the possible load combinations (see 5.5) the requirements are numerated which are applicable in general to concrete storage tanks (see 5.6) and concrete safety walls (see 5.7). Finally, test loads (see 5.8) are discussed.

5.1 Design criteria

In order to determine the design loads to be adopted, the client should - usually in consultation with the public authorities concerned - establish design criteria, taking account of the storage system and of local conditions.

The design criteria are based on:

1. The nature of the liquefied cooled gas, its chemical composition, density, storage temperature, limits of flammability, etc.

2. The gas pressure occurring in the storage tanks in normal use, as well as the maximum overpressure and the maximum underpressure. The magnitude of these gas pressures will depend on the strength of the roof structure and the safety precautions to be installed (e.g., blow-off valves to prevent overpressure, supply of confining gas to prevent underpressure).

3. The quantity of liquefied cooled gas to be stored in each tank.

4. The permissible rate of evaporation in boil-off.

5. The manner in which the test loads are to be applied. In general a tank is tested for strength and rigidity, as well as for liquid-tightness and gas-tightness, before it is put into service. For
this purpose, guidelines are issued by the client and/or the authorities (see 5.8), so that these test requirements can be duly taken into account in the design of concrete structures.

6. Data with regard to the location, such as meteorological data (temperature, precipitation, etc.), the possible aggressiveness of the environment, soil engineering data (geological profile, bearing capacity of the subsoil, groundwater level, etc.), and other relevant information.

7. The undesirable events, of internal and external origin, for which the concrete structures have to be designed (see 5.3 and 5.4). The special loads which may occur in consequence of these undesirable events will, as a rule, have to be laid down in quantitative terms.

5.2 Ordinary loads (in normal use)

By "ordinary loads" are here meant the loads which will occur under normal conditions of operation. For storage tanks a distinction can, with respect to these loads, be drawn between the roof (see 5.2.1), the wall (see 5.2.2) and the base (see 5.2.3). In the case of safety walls of course only the wall structure has to be considered. In designing the concrete structure, basing oneself on the effect of the design loads, it is necessary also to take the following matters into consideration:

a. Material factors:
   - shrinkage and creep of concrete;
   - temperature deformations;
   - relaxation of steel stresses.

b. Structural factors:
   - deviations from circularity of the wall (tanks wholly or partly below ground level);
   - settlement (more particularly, differential settlement) of the subsoil.

These matters, which receive due attention in normal design practice, have not been separately mentioned in the following summarizing enumerations.
5.2.1 Roof structure

The roof structure should be designed for the following loads:
- dead weight, including the weight of installations mounted on or in the roof and of components suspended from the roof, such as insulating blankets;
- snow load (see NEN 3850/TGB 1972) \(1-1\); (see note on page 50)
- wind load
- maximum gas overpressure (to be stated by the client: see 5.1, point 2);
- maximum gas underpressure
- temperature of the space under the roof, i.e., the maximum and minimum temperature difference between this space and the surroundings.

5.2.2 Wall structure

The wall structure should be designed for the following loads:
- any loads transmitted from the roof structure;
- wind load (see NEN 3850/TGB 1972) \(1-1\); (see note on page 50)
- liquid pressure;
- gas pressure;
- frictional forces (if any) due to restrained deformation of the wall in relation to the base or the subsoil;
- temperature influences (both on cooling and on warming up).

With regard to the temperature influences on cooling there are two possibilities:
- the liquid pressure and a temperature gradient act simultaneously, with the result that a maximum tensile stress occurs locally;
- the tank has been emptied, so that the liquid pressure is absent, but the temperature gradient still substantially exists, with the result that a maximum compressive stress occurs locally.
It is also necessary to take account of the loads which occur in the loading tests (see 5.8).

In the various forms of construction in concrete which are envisaged in this report (see Chapter 4) the above-mentioned loads will not in all cases be equally important. Table 6 (page 165) summarizes the ordinary loads relevant to these forms of construction.

5.2.3 Base structure

The base structure should be designed for the following loads:
- loads transmitted from the wall structure (including upward forces due to gas overpressure acting on the roof);
- dead weight, including the weight of tank bottom insulation, etc.;
- weight of the contents of the tank;
- frictional forces (if any) due to restrained deformation;
- temperature influences (both on cooling and on warming up);
- groundwater pressure, more particularly in the case of a tank wholly or partly below ground level.

With regard to the base structure it is likewise necessary to take account of the loads which occur in the loading tests (see 5.8).

5.3 Special loads due to "events of internal origin"

The structure must be able to resist the (special) loads which occur in consequence of undesirable "events of internal origin" (see 2.3.1). This should be indicated by the client (see 5.1, point 7).

5.3.1 Overfilling

The liquid may reach to the upper edge of the wall of the tank (see 2.3.1.3), in which case the liquid pressure will be in excess of the normal value. As a result of reduction in volume of the space above the liquid, the gas pressure may also rise. The client should supply information on this.
5.3.2 **Gas overpressure and underpressure**

The gas pressure occurring in normal operation (excess, i.e., above-atmospheric pressure as well as negative pressure: see 2.3.1.1 and 2.3.1.2) should be stated by the client (see 5.1., point 2). Under special conditions the gas pressure may become higher or lower than these values, and appropriate limits should be agreed with the client. These limits are, inter alia, dependent on the nature of the liquefied cooled gas and on the safety arrangements provided.

5.3.3 **Temperature shock or "cold spot"**

A wall surrounding a storage tank (outer tank or safety wall) may be subjected to a "temperature shock" as a result of overfilling (see 5.3.1), leakage or sudden failure of the tank (see 2.3.1.4).

A, so-called, "cold spot" can appear on the outer tank wall if there are local defects in the insulation between inner and outer tank. In this case important temperature differences will develop in the tank wall, resulting in high stresses and often the initiation of cracks in the concrete.

5.3.4 **Liquid impulse**

If a tank suddenly fails, the wall surrounding it will be subjected to a "liquid impulse". The tank could moreover undergo a displacement and hit the wall. The magnitude of the impact load to be adopted in that case will depend, inter alia, on the distance between the tank and the wall (i.e., the width of insulating cavity or the gap), the depth of liquid in the tank, and the density of the liquid [6-23].

If such a (special) load is to be taken into account, it will often be necessary to ascertain its magnitude by means of tests, as there is as yet no quantitative information available on the subject.

**Note:** The horizontally acting "impact", at right angles to the concrete wall, will set up vibrations in this relatively flexible
wall, because an axial tensile and compressive wave will be produced in it, or a combination of waves. If the concrete wall is to be designed for such conditions, the reinforcement and/or the prestress will have to be so arranged that the structure can absorb these tensile and compressive waves without the occurrence of plastic deformations in the structure. This latter requirement is important, because the concrete wall, after "absorbing" the impact load, will have to act as a liquid-retaining structure. If the concrete has cracked, the cracks will have to close up as soon as the tensile and compressive wave has passed. The presence of a prestress is particularly favourable with regard to this (see 3.7).

The effect of dynamic loads, such as the "impact" forces envisaged here, can be calculated in principle, e.g., by the finite element method. An example of this procedure is embodied in the DIANA computer program, which is based on the displacement method, for static as well as dynamic loads [7-9].

5.3.5 Explosion in a gap (between tank and safety wall)

The possibility of an explosion occurring in the gap must be taken into account. The magnitude of the explosion pressure will depend on the nature of the liquefied cooled gas, the height/width ratio of the gap, etc. Calculation of the pressure build-up will have to be based on information published in the literature, e.g., [6-1] and [6-2]. For a preliminary design calculation a quasi-static one-sided pressure of 0.2 - 0.3 bar may be adopted.

5.3.6 Tank contents on fire

If the contents of the tank catch fire (see 2.4.1), the wall of the tank will have to remain intact, at least below the surface of the liquid. Compliance with this condition must be verified in designing the tank or safety wall.
5.4 Special loads due to "events of external origin"

The structure should be able to withstand the (special) loads due to undesirable "events of external origin" (see 2.3.2). This should be indicated by the client (see 5.1, point 7).

5.4.1 Nearby fire

A storage tank or safety wall should be able to withstand the radiant heat emitted by a nearby fire (see 2.3.2.1). In the event of a pool of liquid having caught fire, this heat radiation can be calculated: \[ 6-1 \] and \[ 6-2 \]. The intensity and duration of the radiation striking the wall will depend, inter alia, upon the height and diameter of the pool of burning liquid and on the distance between it and the wall in question. For other sources of fire the heat radiation can be calculated in similar fashion.

Note: If the duration and intensity of the heat radiation upon the concrete wall are known, the unfavourable temperature distribution in this wall can be determined (see 3.8.2). It can then also be ascertained whether the temperature at the prestressing steel and the anchorages is likely to exceed the permissible value and the permissible duration of this temperature. This duration is connected with limitation of prestress losses. If so, the "concrete cover" to the prestressing steel and anchorages will have to be increased.

5.4.2 Nearby explosion

A storage tank or safety wall must be able to withstand the pressure wave caused by an explosion occurring in its vicinity (see 2.3.2.2). In the event of a gas/air mixture exploding, the shock wave can be calculated \[ 6-2 \]. The formula for the purpose has, however, been derived for a spherical cloud of gas which is detonated (see 2.4.3). For the deflagration of such a gas cloud the calculation is not so simple, and even less so for a non-spherical cloud.
For a preliminary design calculation a quasi-static one-sided pressure of 0.1 - 0.3 bar may be adopted. It will have to be checked that the compressive forces which, as a result of the pressure, are exerted on the tank can be transmitted to the foundation without premature failure of structural components that are vital to ensuring such transmission.

Note: The shock wave produced by a nearby explosion may constitute a critically determinative loading condition for the structure. In consequence of "reflection" by the wall, the horizontal compressive load acting on it will be further increased. Besides, the structure will tend to "overturn", as it were, so that tensile as well as compressive loads are developed which act more particularly at the wall-to-base connection (fig. 35). After the pressure wave has passed, a negative (suction) pressure often occurs, so that the roof, too, is subjected to a suction force. The whole structure (foundation, base, wall and roof, including their structural connections) will have to be designed for the loads envisaged here.

![Diagram](attachment:image.png)

Fig. 35. The shock wave from a nearby explosion causes tensile as well as compressive loads
5.4.3 "Impacts", "hits", etc.

It may be desirable to design a storage tank or safety wall to cope with "impacts", "hits", etc. (see 2.3.2.3 to 2.3.2.5). This should be indicated by the client (see 5.1, point 7).

Note: If undesirable events of this kind are to be reckoned with (see 5.1, point 7), it should be investigated whether the concrete wall is able to absorb the "impact" or "hit" without undergoing "penetration". For calculating the "penetration resistance", and therefore the required minimum wall thickness, appropriate formulas are available (see 3.6). If necessary, the effect of axial compressive and tensile impacts (see 3.7) will also have to be examined.

For these calculations it will, among other information, be necessary to know the weight and size of the "object" liable to hit the structure and also to know the velocity on impact. As for the "flying fragments" hurled away by an explosion, the largest piece of material or equipment liable to be flung in the direction of the tank or safety wall in the event of an explosion in adjacent installations may be taken as the basis for such design calculations.

5.4.4 Natural phenomena and disasters

Depending on the siting (geographic location) of the storage tank or safety wall, the possible occurrence of natural phenomena or natural disasters liable to affect such structures will have to be taken into account (see 2.3.2.6). The effect of a hurricance is comparable to that of an explosion (see 5.4.2) in terms of pressure exerted.

Note: For concrete storage tanks and safety walls no very serious problems are likely to arise from floods. Cylindrical concrete walls are very well able to withstand external pressure. This will, however, have to be verified for each individual case.
5.5 Load combinations and load factors

The ordinary and the special loads (see 5.2 to 5.4) can certainly not all occur at one and the same time. Structures for "unpressurized cooled storage" should therefore be designed for the relevant combination(s) of these loads. The following stages are to be distinguished with regard to this:

1. the construction stage, in which the storage tanks are still empty;
2. the testing stage, in which the tanks are filled with water and/or cooled with liquefied cooled gas;
3. the service stage, in which the tanks are commissioned ("cooldown" by filling with liquefied cooled gas) and are in use;
4. the maintenance stage, in which the tanks are emptied and therefore acquire the ambient temperature, followed later (after maintenance work has been carried out) by another "cooldown" operation.

Load factors for these four stages should be obtained from the existing Netherlands codes and regulations (\[1-1\] and \[1-4\] to \[1-10\]) in so far as these are applicable, or other national recommendations.

5. the "disaster" stage, in which undesirable events of internal or external origin occur. (The client should indicate whether such disasters have to be reckoned with: see 5.1, point 7).

For this last-mentioned stage a load factor of at least 1.1 should be adopted for the limit state of failure. The load factors for the limit states of serviceability will have to be agreed with the client depending on the requirements applicable to the structure after such disasters and depending on the possible consequences of a particular disaster.

For the various forms of construction in concrete which are envisaged in this report (see Chapter 4), combinations of ordinary and special loads will constitute the governing conditions. Table 6 lists a number
<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>C--SIS</th>
<th>C--IS</th>
<th>C_{L}I--S</th>
<th>C_{L} IS</th>
<th>C_{L}IC_{L}</th>
<th>SIC_{L}</th>
<th>CIL</th>
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<td></td>
<td></td>
<td>see 4.3</td>
<td>see 4.4</td>
<td>see 4.5</td>
<td>see 4.6</td>
<td>see 4.7</td>
<td>see 4.8</td>
<td>see 4.9</td>
<td>see 4.10</td>
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</tr>
<tr>
<td>15.</td>
<td>impacts, hits, etc.</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

s = safety wall; ou. = outer tank/outer wall; in. = inner tank/inner wall

* Quantitative information with regard to these items should be provided by the client, often in consultation with the public authorities concerned.

It is assumed that the "disasters" (9 to 15) will not occur simultaneously.
of possible combinations. Only the wall structures are considered (safety walls and the walls of outer and inner tanks). Similar tables can be compiled for foundation, base and roof structures.

5.6 Requirements applicable to concrete storage tanks

5.6.1 Tank walls

The liquid-retaining walls of tanks are built of prestressed concrete. For tank walls surrounded by earth, reinforced concrete construction may be considered in particular cases. Design, analysis and construction should conform to the (Netherlands) Code of Practice for Concrete, the so-called Voorschriften Beton 1974 (NEN 3861 to 3867) (1-4) to 1-10), more particularly Part F "Prestressed concrete" (NEN 3866) 1-9). See note on page 50. In addition, the following supplementary requirements have to be fulfilled:

1. For the materials to be used (prestressing steel, reinforcing steel, concrete, etc.) it must be known, or be determined by means of tests, how they behave at the low temperatures to which they will be exposed under normal and abnormal conditions. The properties that are of especial importance in this context are strength, rigidity, deformability, toughness (steel), coefficient of thermal expansion, etc. Special attention should be given to the behaviour of the anchorages and the reinforcing steel that will be employed. If necessary, special grades of steel should be used for reinforcement; prestressing steel may sometimes suitably be used as (untensioned) reinforcing steel.

2. The concrete wall should be liquid-tight.

3. If the wall also has to be vapour-tight, a vapour barrier or a liner should be installed. A steel liner should, if necessary, be anchored to the concrete in order to prevent it from being pulled away on cooling. The liner should, if possible, be installed in the concrete wall. A steel liner attached to the inner face of the concrete wall is not advisable.
4. The concrete cover to the prestressing steel should be sufficient to ensure that, in the event of a fire in the vicinity, the temperature in this steel will not rise above 200 °C, lasting not longer than about 6 hours. A similar requirement is applicable to the cover to the anchorages, having due regard to their behaviour on exposure to high temperatures.

5. The prestressed concrete wall should be designed for all loads and load combinations that are significant with respect to this wall.

5.6.2 Tank bases

The requirements applicable to tank bases are in principle the same as those applicable to tank walls (see 5.6.1). However, in view of the loads acting on the base, it will usually not be necessary to use prestressed concrete.

5.6.3 Wall-to-base connection

The connection of the wall to the base should be so designed that the expected deformations of the wall in relation to the base (and those of the base in relation to the wall) can be accommodated without causing damage to the structure. If the wall and the base are rigidly joined together, it should be ensured, however, that the stresses caused by restrained deformations will nowhere exceed the relevant permissible values and, in addition, that the durability of the connection in question is preserved.

5.7 Requirements applicable to concrete safety walls

5.7.1 Dimensions

The space enclosed by the safety wall should be of such size that it can hold the contents of the actual storage tank. Some excess height of the safety wall is desirable for this purpose, for otherwise the liquid flowing out of the storage tank in the event of sudden failure of the latter will not only impinge upon the safety
wall, but some of it may spill over it. It appears advisable not to make the safety wall lower than the maximum height of the liquid in the storage tank.

If the possible occurrence of a fire or explosion in the vicinity of the safety wall has to be taken into account, it is advisable to build this wall to such a height that it encloses the entire tank (including the roof). In this way, damage to the roof by a nearby fire or explosion can be prevented.

5.7.2 Supplementary requirements

The supplementary requirements are bound up with what is expected from the safety wall.

1. If cold liquid comes into contact with the safety wall ("cold shock"), the wall should remain under compressive stress over at least one-third of its thickness, reckoned from the outer face. For checking this, the temperature distribution (temperature gradient) through the wall, and the stresses caused by this distribution, should be calculated. For this calculation the values for the thermal expansion coefficients of concrete and steel for the temperatures under consideration should be adopted.

2. The safety wall should be designed for:
   - a "liquid impulse" occurring in the event of sudden failure of the storage tank;
   - a "cold shock" occurring in the event of sudden failure of the storage tank;
   - a possible explosion in the gap (the storage tank itself should also be designed for this occurrence);
   - the heat radiation from a possible fire in the vicinity;
   - the shock wave caused by a possible explosion in the vicinity.

In connection with these loads the safety against overturning of the wall should also be checked. Besides, it must be ensured - by means of special arrangements (e.g., impact kerbs) - that
special horizontal loads can also be transmitted to the foundation. The client should, possibly in consultation with the public authorities concerned, indicate whether supplementary requirements are applicable with regard to "impacts", "hits", etc.

3. The connection of the safety wall to the base of the gap should be, and remain, liquid-tight, even if the wall undergoes considerable cooling in the event of outflow of liquid from the storage tank.

4. Ingress of water into the gap should be prevented. To ensure this, the gap may be provided with a covering or the roof of the tank be extended outwards over the gap. Any water that does get into the gap should be removed. Manholes with valves may be installed for this purpose: the materials of which these are made should be resistant to low temperatures so as not to develop leakage on coming into contact with cold liquid. Alternatively, a sump for pumping out the liquid through a pipeline passing over the safety wall may be provided.

5. The distance between the safety wall and the actual storage tank should be large enough to allow proper inspection of the tank. For this reason the gap will have to be at least 1.5 - 2 m wide. (The industrial inspection authorities may insist on a larger width).

6. No pipes should be allowed to pass through the safety wall. (An exception may be the manholes with valves mentioned in point 4).

7. Certain technical operating requirements will also have to be fulfilled by the gap, e.g., in connection with the gas detection system or inertization. Such requirements are outside the scope of this report, however.

5.8 Test loads

Before a new storage tank structure is commissioned, loading tests will have to be performed. In principle, there are three possibilities: the "water test" (see 5.8.1), the "gas test" (see 5.8.2) and the "cooling test" (see 5.8.3).
5.8.1 "Water test"

For this loading test the tank is filled with water until the load on the base of the tank is equal to 1.25 times the working load. In some cases a water test is required by which the tank is completely filled with water. In this way the liquid-tightness of the tank wall and base the wall-to-base connection and the other structural features as well as pipelines, etc. can be checked. The loads of the water test have to be taken into consideration in the design.

Besides, with the load thus applied, the "primary settlement" can be induced, while the behaviour of the foundation can also be observed. When the inner tank has been filled with water, the insulation cavity (if any) and the gap can also be filled with water in order to check their liquid-tightness. In the case of the insulation cavity this will of course be done before the insulating material is installed. After removal of the water from this cavity, it should be thoroughly dried out before the insulating material can be introduced into it.

5.8.2 "Gas test"

For this loading test the tank is filled with gas at a certain pressure, which is checked with the aid of pressure gauges. The gas employed for the purpose may, for example, be air or another inert gas. If there is found to be a loss of pressure, it means there is a leak somewhere, which will have to be located. In this test it should be borne in mind that there may be differences in properties, e.g., viscosity, between the inert testing gas and the gas subsequently formed by evaporation of the liquid stored in the tank.

5.8.3 "Cooling test"

In this loading test, which is entirely similar to a normal "cool-down operation" on commissioning the tank, liquefied cooled gas is evaporated in the storage tank. This is done under fully controlled conditions, i.e., in such a way that the temperature in the tank and the tank structure goes down gradually to the same temperature as will occur when the tank is subsequently in actual use.
In carrying out the test, temperature measurements are performed (e.g., in the wall or only on the inside or the outside thereof) by means of which the temperature variation behaviour in the structure is monitored. In this way it can more particularly be checked that the insulation meets the appropriate requirements. A visual inspection should also be carried out for this purpose. Thus, if ice formation is found to occur on the outside of an insulated wall, this will be an indication that the insulation is locally not functioning properly.

5.9 Summary

The requirements as to the loads and safety factors applicable to a concrete tank are conveniently summarized in Table 7 on page 171. The figures listed there provide guide values for the loads to be adopted and for the associated load factors. Obviously, the loads to be adopted in the calculations will vary from one case to another. The load factors to be introduced will also vary from one structure to another because the consequences of a special load are likely to differ on account of all sorts of circumstances.

However, it is of considerable practical importance to have some indication of the order of magnitude of these loads and load factors in preparing a preliminary design. For in this way it will be possible to obtain an idea of the significance of the relevant special loads with regard to the dimensions of the structural members.

Subject to the proviso that the values given here are intended for tentative guidance only, and lay no claim to constituting any generally-valid rule, it has been endeavoured to meet practical requirements by giving the information on the loads, especially suitable for LNG-tanks, and their associated load factors, contained in Table 7. The material coefficient in the factor of safety has been taken as equal to 1 (unity).
Table 7. Summary of approximate guide values for loads and load factors to be adopted in the design

<table>
<thead>
<tr>
<th>Loading by:</th>
<th>Section</th>
<th>Of importance of:</th>
<th>Magnitude of load</th>
<th>Load factor</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dead weight, Wind, Snow, Liquid</td>
<td>5.2</td>
<td>✔     ✔ ✔ ✔</td>
<td></td>
<td>1.0</td>
<td>1.7 1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Load combinations should also be considered, see Table 6</td>
</tr>
<tr>
<td>Gas overpressure</td>
<td>5.2</td>
<td>✔     0 0 ✔</td>
<td>national codes of practice</td>
<td>1.0</td>
<td>1.7 1.7</td>
</tr>
<tr>
<td>Gas underpressure</td>
<td>5.2</td>
<td>✔     0 0 ✔</td>
<td></td>
<td>1.0</td>
<td>1.7 1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Testing phase</td>
<td>5.8</td>
<td>✔     0 ✔ ✔</td>
<td>1.25 full load</td>
<td>-</td>
<td>1.2 - -</td>
</tr>
<tr>
<td>Loading test with water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Special</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overfilling</td>
<td>5.3.1</td>
<td>-     - ✔ ✔</td>
<td>full to top of wall</td>
<td>-</td>
<td>1.2 1.5 -</td>
</tr>
<tr>
<td></td>
<td>5.3.2</td>
<td>✔     0 - ✔</td>
<td>-0.02 bar 1)</td>
<td>-</td>
<td>1.2 1.5 -</td>
</tr>
<tr>
<td></td>
<td>5.3.2</td>
<td>✔     0 0 ✔</td>
<td>+0.3 bar 1)</td>
<td>-</td>
<td>1.2 - 1.5</td>
</tr>
<tr>
<td>Roll-over</td>
<td>5.3.2</td>
<td>✔     0 0 ✔</td>
<td>+0.5 bar 1)</td>
<td>-</td>
<td>1.1 - 1.3</td>
</tr>
<tr>
<td>Spill 2)</td>
<td>5.3.3</td>
<td>✔     ✔ ✔ ✔ ✔</td>
<td>15 m 3)</td>
<td>-</td>
<td>1.4 - -</td>
</tr>
<tr>
<td>Liquid impact</td>
<td>5.3.4</td>
<td>✔     (5) ✔</td>
<td>6 x hydrost.</td>
<td>-</td>
<td>- - -</td>
</tr>
<tr>
<td>Temp. impact</td>
<td>5.3.3</td>
<td>✔     (6) ✔</td>
<td>temp. of liq.</td>
<td>-</td>
<td>- - -</td>
</tr>
<tr>
<td>Explosion outside</td>
<td>5.4.2</td>
<td>✔     ✔ ✔</td>
<td>0.2-0.3 bar 8)</td>
<td>-</td>
<td>1.1 1.5 1.5</td>
</tr>
<tr>
<td>Explosion in gap</td>
<td>5.3.5</td>
<td>✔     ✔ ✔</td>
<td>0.2-0.3 bar 8)</td>
<td>-</td>
<td>1.5 1.5 1.5</td>
</tr>
<tr>
<td>Impact from heavy object</td>
<td>5.4.3</td>
<td>✔     ✔ ✔ ✔ ✔ ✔  ✔</td>
<td>heaviest fragment 9)</td>
<td>-</td>
<td>- - -</td>
</tr>
<tr>
<td>Sabotage</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Impact from aircraft</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Fire outside</td>
<td>5.4.1</td>
<td>✔     ✔ ✔ ✔</td>
<td>temp. of 10)</td>
<td>-</td>
<td>1.1 - 1.1</td>
</tr>
<tr>
<td>Fire inside</td>
<td></td>
<td></td>
<td>prestr. steel</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.4.4</td>
<td>✔     0 ✔ ✔</td>
<td>200 °C</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

1) uniformly distributed load
2) or leakage of insulation
3) area of "cold spot"
4) crack depth to 0.5 hₜ
5) only with open gap and possibility of ripping-open of inner tank
6) same condition as 5), but only if there is no permanent internal insulation
7) crack depth to 0.7 hₜ
8) locally acting impact; check also for overall movement of tank
9) velocity of object determined by intensity of explosion
10) this temperature is not to occur for longer than about 6 hours
11) tank must remain intact until it has burnt itself out
Abbreviations in the table:

- **roof** = roof of the tank
- **ouw** = outer wall
- **inw** = inner wall
- **base** = base of the tank
- **dec** = decompression

  the concrete stresses in the tensile zone are zero
  \[ \sigma_c = 0 \]

- **fi cr** = first crack

  the concrete stresses in the tensile zone are of the
tensile strength of concrete.
  \[ \sigma_c = f_{cc} \]

- **fa comp** = failure due to compressive crushing of the concrete

- **fa tens** = failure due to tensile fracture of the steel

• for this case the indicated load is applicable

0 for this case the indicated load is applicable only under certain
conditions (for example: ouw = safety wall, etc.).
Peak-shaving Plant - Nederlandse Gasunie - Maasvlakte - Rotterdam Europort
Horizontal and vertical prestressing with tendons in ducts, grouted after prestressing
Information page 232
6 STRUCTURAL ARRANGEMENTS AND DETAILS

In this chapter an approximate overall description will be given of the structural arrangements and details of concrete structures for "unpressurized cooled storage". The purpose of this description is merely to give the reader a proper understanding of the various problems that this involves. It is not, therefore, the intention to deal in much detail with all kinds of structural components.

6.1 Foundation structures for concrete tanks

6.1.1 General

Concrete structures in general possess much greater stiffness, or rigidity, than steel structures. Differential settlement of the subsoil is therefore liable to cause greater stress concentrations in structures built of concrete than in those built of steel. In order to prevent this, the foundation and its supporting medium should be much more rigid for concrete than for steel tank structures. For this reason the foundations of the former will often be substantially more expensive than those of the latter.

For the design of a foundation structure that meets the said requirements of strength and rigidity it will be necessary to carry out thorough soil mechanics investigations on the actual site of construction. These investigations should provide the information that the concrete designer requires (see 5.1, point 6).

It must be ascertained where the loadbearing strata are situated and what their load capacity is. The composition of the various strata must be determined. The groundwater level, with its highest and lowest values, should be known.

The soil mechanics investigations will also have to enable a prognosis to be made of the settlement, and especially the differential settlement, that can be expected to occur. This information is of major importance with regard to the choice of structure and the detailing thereof.
For the foundations of tank structures a distinction is to be drawn between "raft foundations" (see 6.1.2) and "pile foundations" (see 6.1.3).

6.1.2 Raft foundation

A "raft foundation" is a direct-bearing "shallow" foundation, i.e., it rests directly on the loadbearing stratum or strata. This type of foundation, which often takes the form of a concrete slab, can be employed under the following circumstances:

a. The loadbearing stratum is situated only a short distance below ground level:
   The vertical loading exerted on the subsoil by tank structures is generally in the range of 150 - 250 kN/m² (15 - 25 t/m²). Only stable and densely packed soil strata are capable of supporting a loading of this magnitude.

b. The soil condition is such that only small amounts of settlement will occur under the given loads and that such settlement will attain its final value already within a short period.

c. The composition, homogeneity, etc. of the subsoil are such that no major differential settlement is to be expected and no surfaces of sliding will develop.

For a tank structure the foundation may consist of a concrete slab, which is usually provided with ribs serving, among other functions, to carry the concrete wall(s) resting on the slab (fig. 36).

Under a tank in which (very) cold liquid is stored, frost is liable to penetrate gradually into the soil because heat is extracted from it. This may result in undesirable "frost heaving". In order to obviate these phenomena it will be necessary to introduce so much heat under the tank that no freezing can occur. The capacity of the heating system for this purpose has to be adjusted to the permissible rate of "boil-off", the storage temperature (more particularly, the cold capacity) of the tank contents, the insulation of the tank base, etc.
The pipes serving the system should be so designed that they offer the possibility of checking its proper functioning and of replacing or repairing it, should that become necessary.

In order to prevent penetration of moisture into the foundation slab, a vapour-tight layer should be provided under the slab (i.e., on the surface of the blinding or mat which forms the bed on which the slab is laid: see fig. 36). This layer, which may be of bituminous material for example, should be protected from possible damage during the construction work.

The problems outlined above can largely be obviated by installing the base of the tank at some height above ground level. To this end, the base slab is mounted on short concrete columns which stand on the foundation slab. This solution has much in common with a pile foundation (see 6.1.3), to which reference should be made for further information.
6.1.3 Pile foundation

If the loadbearing strata are at considerable depth below ground level, the load from the tank structure will have to be transmitted to them through concrete piles. These may either be precast piles or cast-in-situ piles. In view of recent developments in cast-in-situ piles with high load capacities it is likely that such piles will frequently be used for the construction of tank foundations.

With a pile foundation an obvious arrangement is to keep the underside of the base slab of the tank clear of the surface of the ground, i.e., to give it some elevation above ground level (fig. 37). This will enable the underside to be inspected, and a heating system (with its attendant difficulty of access for maintenance, etc.) to be dispensed with.

Fig. 37. Example of a pile foundation
For proper access for inspection of the underside of the tank a free headroom of about 2 m is desirable. The natural ventilation in this type of cavity prevents freezing and "frost heaving" of the soil, so that no heating is needed. This ventilation will also virtually rule out any possibility of a so-called critical gas/air mixture being formed in the cavity under the base. All the same, gas detectors for monitoring this hazard should be installed.

In this solution the vapour-tight layer is usually installed on the upper face of the concrete slab (fig. 37) and can in most cases be identical with the vapour-tight layer associated with the storage system itself. For information on the function of this layer see 6.5.

The connection between the base slab and the pile heads may be a rigid one ("monolithic") or be so constructed that a certain amount of differential horizontal movement between the piles and the base is allowed. The choice between these alternatives is determined by the stiffness of the piles in relation to the magnitude of the expected displacements, horizontal loads and any (special) external loads that have to be taken into account.

In the case of piles with high load capacity, which usually possess considerable stiffness (rigidity against deflection), a "sliding bearing" will often be preferred. For this purpose a suitable bearing material is interposed between the concrete slab and the piles on which it is supported. This type of bearing allows differences in displacement between the pile heads and the base slab; its structural detailing and its execution accordingly require considerable care.

In a case where piles of greater flexibility (i.e., possessing less stiffness) are installed in soft ground, a rigid ("monolithic") connection between the base slab and pile heads may be preferable. If the tank structure has to be so designed that it can resist large horizontal loads (e.g., due to an explosion), it will even be essential to connect the base slab rigidly to the piles. In such cases it will be important to check whether the whole tank-cum-
foundation assembly is indeed so rigid that, on being subjected to impulses from explosions, no displacements will occur that are liable to set up a kind of wave motion in the contents of the tank. A rigidly mounted concrete tank will act as a suitably rigid body in absorbing and coping with explosion pressures.

If the choice is made in favour of a monolithic connection of the base slab to the pile heads, this slab will have to be designed for the pattern of forces that arises in effecting the transfer of horizontal (impulse) loads. The designer will more particularly have to think of bending moments, whether or not in conjunction with punching shear.

6.2 Wall-to-base connection

6.2.1 Deformations of the tank wall of prestressed concrete

A concrete tank wall can undergo deformations due to a variety of causes:

a. After concreting, i.e., during the setting and hardening of the concrete, some shortening (shrinkage) will occur in consequence of physico-chemical processes. As a rough indication this early shrinkage strain will be of the order of 10 to 20 x 10^{-5}.

b. As a result of prestressing, i.e., placing the concrete under compressive stress, elastic shortening of the tank will occur in the tangential and therefore also in the radial direction. The order of magnitude of this shortening is 5 to 15 x 10^{-5}.

c. In course of time there occur further shortening of the hardened concrete due to long-term shrinkage and creep. The order of magnitude of the shrinkage strain can be taken as 10 to 20 x 10^{-5} and that of the creep strain as 10 to 30 x 10^{-5}. These shortening effects develop during the course of several years, but the rate at which they develop diminishes as time goes by, so that they tend to a certain final value.

d. In consequence of daily and seasonal variations in the air temperature, thermal shortening (contraction) occurs.
e. In the "cooldown operation" on commissioning the tank and in the "cooling test" (see 5.8.3), shortening (contraction) will occur in the concrete of a primary tank and of comparable other concrete structures. The magnitude of this shortening will depend on the average fall in temperature of the concrete and of course on the coefficient of thermal expansion. If a safety wall or other concrete structure suddenly comes into contact with cold liquid in consequence of an undesirable event, contraction of the concrete will likewise occur, but now within a relatively short time, i.e., at a rapid rate.

f. The loads acting on the tank wall will of course also cause deformations (strains) in the concrete.

If all the above-mentioned causes (a to f) exercise their respective effect, the resulting amount of shortening may be quite substantial. Even only the causes a, b and c may, in a concrete tank of 50 m diameter, cause a reduction in diameter of 20 - 40 mm in the case of unrestrained deformation of the wall.

The deformations of the base slab in the radial direction will usually be much smaller than those of the tank wall. The wall-to-base connection should therefore be so designed as to allow these differences in deformation to occur, which means that this connection will have to fulfil special requirements. If the wall-to-base connection is of such construction as to prevent the deformations of the wall in relation to the base, this restraint will cause large forces to develop in the vicinity of the connection, and these forces will duly have to be taken into account, as they may considerably affect the pattern of stresses in connecting parts of the structure.

6.2.2 Wall standing on base slab

If the tank wall stands on the base slab, the wall-to-base connection may be formed in one of three different ways: a rigid connection; b hinged connection; c sliding connection.

a Rigid wall-to-base connection (fig. 38a):

A rigid connection of the foot of the wall to the base is possible
only on condition that the respective deformations of wall and base, if these two members were unrestrained, differ little from each other; otherwise forces of such large magnitude will be set up in the structure that they cannot be adequately resisted. This condition is satisfied, inter alia, by concrete walls with approximately the same temperature as the surroundings of the tank. This situation can be achieved by separating the concrete tank wall from the cold liquid by the interposition of effective insulation.

Having regard to the above-mentioned condition and the manner in which it can be satisfied, the rigid wall-to-base connection will be a suitable choice only for tanks with limited dimensions, for tanks in which the stored liquid has a temperature not much below 0 °C, and for tanks which are so insulated that the wall and base will undergo only a slight lowering of temperature.

Fig. 38. (a) rigid, (b) hinged and (c) sliding wall-to-base connection

An important advantage of the rigid connection, and also of the hinged connection described below, is that it ensures a high
degree of positive positional location of the wall foot and, in addition, enables large horizontal forces (e.g., due to an explosion) to be transmitted to the base slab.

b. Hinged (or pinned) wall-to-base connection (fig. 38b):

A "concrete hinge" ("pin joint") may be formed at the junction of the wall foot and the base slab. In this way the above-mentioned advantage of a rigid connection is preserved, but the rotational movement allowed by the hinge action will substantially reduce the so-called meridian moments. All the same, this type of connection is possible only if the respective unrestrained deformations of wall and base do not differ much from each other.

c. Sliding wall-to-base connection (fig. 38c):

With a sliding connection the wall stands on the base, but with the interposition of a bearing material which allows differences in horizontal displacement to occur between these two members, besides allowing rotational movements. The frictional forces due to the horizontal displacements cause bending moments in the wall and in the base. These forces, and therefore the moments associated with them, can be reduced by using a bearing material that offers only a low frictional resistance.

A sliding wall-to-base connection which practically transmits only vertical forces should be so designed that it will continue to function properly even when in contact with cold liquid. This aspect should also be taken into consideration in choosing the bearing material.

The various possibilities for forming the connection call for the following comment.

Both the rigid and the hinged connection (see a and b) have the advantage that the insulation on the inside of the tank wall at this connection undergoes little or no deformation. Besides, both types of connection can be made liquid-tight and vapour-tight by simple means. Also, the tank wall is positively located in relation to the base slab.
On the other hand, a sliding connection (see c) is much more complicated, more particularly because it will have to remain liquid-tight and vapour-tight despite the (permissible) horizontal displacements of the wall and base in relation to each other. Furthermore, the insulation will have to be capable of adapting itself to those displacements at the wall-to-base connection. Finally, it will often be necessary to take additional measures to ensure the positional location of the tank wall within certain limits.

**6.2.3 Wall extending past base slab**

Instead of standing on the base slab (see 6.2.2), the concrete wall may extend down past it. This arrangement is quite feasible for safety walls which are built around existing tanks, the latter usually being steel tanks (C-SIS system, see 4.3). This solution can also be used with C-IS and CI-S (see 4.4 and 4.5).

In these cases the steel tanks can be provided with foundations of the usual type. The foundation is structurally unconnected to the concrete wall (fig. 39) and can therefore undergo settlement independently thereof. However, settlement movements of the foundation may affect those of the concrete wall.

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**Fig. 39. Wall extending past the base slab**
Separation of the foundation of the safety wall from that of the steel storage tank is suitably possible if the loadbearing subsoil strata are not too far below ground level. If those strata are situated at greater depth, a combined pile foundation to support both the wall and the tank may be considered.

In the solution with the wall extending past the base slab, the joint separating these two members should allow not only vertical, but also horizontal, differences in deformation between them to occur (see 6.2.1). At the same time, the joint should remain liquid-tight and vapour-tight. In the CI--S system it must, in addition, be ensured that the wall insulation remains properly connected to the insulation of the base.

On account of the horizontal shortening of the wall (see 6.2.1), it will tend to undergo displacement in relation to the subsoil. If the latter exercises restraint which prevents such displacement, stresses will be set up in the wall of the tank. This aspect should be given due attention in designing and detailing the structure.

6.2.4 Sliding wall-to-base connection (design criteria)

A sliding connection between the wall and the base has to satisfy the following conditions:

a. The connection should enable the differential displacement of wall and base to occur and should be able to transmit vertical, and in certain cases (see 6.2.2) also horizontal, loads.

b. The joint should be liquid-tight, even under heavy liquid load, as occurs when the tank is full.

c. The joint should be vapour-tight. In the case of the CI--S system the presence of gas in the gap must be taken into account: this gas exerts a certain pressure which acts also on the joint structure.

d. The joint structure should be resistant to low temperatures, i.e., the storage temperature, in all circumstances where its exposure to such temperatures cannot be ruled out.
e. In certain cases the connection will have to be so designed as to provide a backing for continuing the insulating material across the wall-to-base joint.

f. In certain cases the connection at the joint will also have to be able temporarily to transmit large locally acting horizontal forces, such as may occur, inter alia, in the following circumstances:

- failure of the inner tank;
- explosions in the gap (if any);
- explosions outside the tank.

If the connection is in principle of the sliding type, it will hardly be the most suitable form of construction for the transmission of horizontal forces, the more so as such transmission will be attended by horizontal displacements (see 6.2.7).

g. The connection must be durable.

6.2.5 Liquid-tightness and vapour-tightness (sliding connections)

The joint at the wall-to-base connection should remain liquid-tight and vapour-tight, despite the (permitted) deformations. From research and from experience in actual practice it has emerged that this can be achieved with membranes made of chrome-nickel steel, stainless steel, etc. The membrane should be connected to the wall as well as to the base in such a manner that its junctions with these members are liquid-tight and vapour-tight. More particularly, at the wall-to-base joints the membrane must be connected to the liquid-tight and vapour-tight sealing system of the wall. Since it is not advisable to install a steel liner on the inside of the concrete wall (see 4.5), this tight connection will have to be formed in some other way. The following solutions are available for the purpose:

a. The membrane is connected to a liner installed in the concrete wall; this liner may be of carbon steel (fig. 40a).

b. The membrane is connected to a liquid and vapour barrier incorporated in the wall in conjunction with the bearing element (fig. 40b).
c. The membrane is connected to a base plate which can undergo deformation independently of the concrete base, more particularly a continuation of the steel tank (fig. 40c).

d. The membrane is connected to a connecting strip incorporated in the concrete wall (fig. 41). This solution is suitable if no steel liner is installed in the concrete wall or if a vapour-tight membrane of plastic is provided on the inside of that wall. The above-mentioned connecting strip should be embedded in the concrete wall with considerable care. An obvious choice is to combine the installing of this strip with a special construction joint arranged for the purpose.

The form of wall-to-base connection shown in fig. 41 is intended merely as an indication of the arrangement that may be adopted in a case where a safety wall extends past the base slab (see 6.2.3). The "special construction joint" is intended specifically for accommodating the connecting plate, which is bent up and form a kind of liner of limited height in the concrete wall.
Fig. 41. Possible solution for forming the joint at the wall-to-base connection of a safety wall with a membrane

The "jointing membrane", at the joint, is welded to the connecting plate and to the base plate. The connecting plate interrupts the reinforcement only near the inner face of the concrete wall; the rest of the reinforcement, as well as the prestressing tendons, are behind that plate.
The plastic membrane, on the inside of the concrete wall, overlaps the connecting plate and therefore also the "jointing membrane". The latter should be so shaped and dimensioned that it presents no restraint to narrowing of the joint nor to differential settlement. Besides, it must be able to transmit the load exerted upon it by the liquid to the wall and base.

6.2.6 Transmission of vertical loads (sliding connections)

A sliding wall-to-base connection has to transmit almost exclusively vertical loads. This function imposes special requirements upon the bearing structure and the bearing material, which have to remain functional even when in contact with cold liquid.

Fig. 42. "Sliding" wall-to-base connection, as used for the LNG tanks at Staten Island, New York [8-6]
Fig. 42 shows a solution providing a very limited possibility of movement, which has been used in the United States, and fig. 43 shows the sliding plate bearing system used for two LNG tanks in the Maasvlakte scheme.

![Diagram of sliding plate bearing](image)

Fig. 43. Sliding plate bearing, as used for the safety walls of the LNG tanks in the Maasvlakte

6.2.7 Transmission of horizontal forces (sliding connections)

A sliding wall-to-base connection should, if necessary, be able to withstand and transmit (large) horizontal forces. Such forces may occur in consequence of "undesirable events" such as nearby explosions, "impacts" and "hits", etc. They are usually of short duration.

If the wall stands on the base slab (see 6.2.2), it will be necessary to provide an "impact-resisting kerb" along the edge of the slab (fig. 44), such as is used in conjunction with, inter alia, safety walls. This kerb will have to be so designed that it can transmit the horizontal forces from the concrete wall to the base slab. The
forces in question may be of very considerable magnitude if they are exerted by the wall actually in motion, as a result of horizontally acting impulses.

Fig. 44. "Impact kerb" which should enable the wall-to-base connection to resist horizontal forces and transmit them to the foundation.

It is evident that in all cases where large horizontal forces are liable to occur the sliding connection at the foot of a wall standing on the base slab is not a favourable solution. In such circumstances the wall extending past the base slab (see 6.2.3) may offer a better alternative, which does not require any such additional arrangement as a kerb, since the counteracting pressure of the earth against the bottom part of the wall is able to resist the forces in question.
6.3 Wall structures

6.3.1 Prestressing and reinforcing

Tank walls and safety walls must be able to resist all sorts of temperature stresses and must remain liquid-tight. To enable them to do this, a compressive stress has to be produced in these walls, i.e., they must be prestressed (see 3.8.2). This prestress, which also offers other advantages, should be applied vertically as well as horizontally. Prestressing steel is used, which preserves its particularly favourable properties even at low and very low temperatures (see 3.2.3).

Besides prestressing tendons (in the vertical and in the horizontal direction), reinforcing steel bars have to be installed in a concrete wall. This reinforcement serves to prevent cracking of the concrete in the period immediately after it has been placed. It should, if necessary, also limit the cracking that may occur in the event of "undesirable events" giving rise to "impacts", "hits", etc. (see 3.6), temperature variations and temperature shocks (see 3.8), etc.

If the reinforcing steel is, or is liable to be, exposed to (very) low temperatures, it should be of such quality as to still be able to perform its function at those temperatures. For this reason it will often not be possible to use ordinary reinforcing steel. Special grades of steel will then have to be used instead or, alternatively, prestressing steel may be used as (untensioned) reinforcement (see 3.2.2 and 3.3).

6.3.2 Location and nature of the prestress

The vertical tendons will be installed a little off-centre in relation to the thickness of the wall. The anchorages of these tendons must be so detailed as not to locally impair its liquid-tightness.

The location of the horizontal tendons will be chosen on the basis of the following considerations:
a. In the event of a "temperature shock", i.e., a severe temperature gradient occurring after a "cold shock", the cracks then occurring (both horizontal and vertical) must not be allowed to penetrate to the prestressing steel, which means that this steel should be located within the outer third of the wall thickness (fig. 45). Safety walls and outer tanks may be subjected to such "temperature shock" if the storage tank begins to leak or fails.

Fig. 45. Cracking in a prestressed concrete wall which comes into direct contact with cold liquid
b. During a fire in the vicinity, the "concrete cover" to the pre­
stressing steel and to the anchorages (if any) should be suf­
icient to prevent the temperature in these components from
rising too high during a long period (fig. 46)

Fig. 46. Temperature distribution in a concrete wall due to thermal
radiation. The tendons should be so placed in the wall
that the temperature directly adjacent to them will not
exceed 200 °C and lasting not longer than about 6 hours.

More particularly in the event of "special loads" which may affect
safety walls and tank walls the behaviour of prestressed concrete
will depend also on the bond between the prestressing steel and
the surrounding concrete (or the grout in which this steel may be
embedded). This applies, for example, to the behaviour under axial
compressive or tensile impact loads (see 3.7).
6.3.3 **Steel liner**

In order to obtain the desired vapour-tightness it may be necessary to install a steel liner in the concrete wall. The liner is disposed as close to the outside of the wall as possible, so long as there is enough space left to accommodate the horizontal prestressing tendons (fig. 47). In this way good co-operation between the liner and the concrete wall is obtained.

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**Fig. 47. Location of tendons in relation to a steel liner**
It is known that in reinforced concrete, in consequence of shrinkage and creep of the concrete, a stress redistribution occurs, as a result of which the concrete stresses are reduced [7-3] and [7-11]. A liner in a prestressed concrete wall may have an effect similar to that of reinforcing steel. It should therefore be verified beforehand whether and, if so, to what extent this effect is likely to occur, so that it can be taken into account.

A liner embedded in the concrete wall is preferable to a liner attached to the inside of the wall. The latter solution is generally not to be recommended. If it is adopted, the liner should be securely fixed to the wall by means of anchor bolts or dowels (loaded in tension) in order to resist possible differences in temperature between liner and wall.

If the steel liner is installed within the thickness of the concrete wall, it must be ensured that both faces of the liner are in complete contact with the concrete. This is adequate to realise in a structure with prefabricated concrete wall elements.

In some systems a vapour-tight layer will be applied to the inside or the outside of a concrete wall, sometimes in combination with the insulating layer. The vapour-tight layer should remain firmly attached to the concrete under all circumstances. This is something which, if not known for certain beforehand, must be established by means of tests.

6.3.4 Pipes.

It is not permissible for steel pipes to penetrate concrete walls. In the event of sudden cooling of such a pipe, it would almost certainly pull away from the concrete, so that a leak would occur, which is something that is especially undesirable under extreme conditions.
6.4 Roof structures and wall-to-roof connections

6.4.1 Roof structures

The roof structure of a storage tank may be of steel or of concrete. Steel roof structures will not be considered in this report. A concrete roof is usually built in the form of a so-called spherical shell.

Fig. 48. Edge beam of a concrete roof structure

This shell (i.e., a spherically curved concrete surface) terminates in an edge beam at its intersection with the concrete wall of the tank (see fig. 48). The beam has to perform, as it were,
the function of the non-existent portion of the sphere of which the roof can be conceived as a segment. In performing this function the edge beam is subjected to large tangential tensile forces which are in equilibrium with the compressive forces transmitted from the spherical shell to the edge. In order to resist these tangential forces as well as the forces caused by temperature differences, the beam is prestressed with a so-called ring prestress.

A concrete roof structure is heavier than one constructed of steel. This is not a disadvantage, but an advantage of the concrete structure, as it enables a higher gas pressure to be allowed in the storage tank. Besides, a concrete roof offers a high degree of resistance to impact from flying fragments, "hits", shock waves from nearby explosions (including the suction forces associated with these), etc.

In order to obtain the desired vapour-tightness a steel liner may be installed on the underside of the concrete roof, at least if the temperature directly under the roof is not too low. Such a liner may serve a useful auxiliary purpose in connection with the construction of the concrete roof (see 8.1.4).

6.4.2 Connection of concrete wall to steel roof (fig. 49)

If a concrete tank is provided with a steel roof structure, the wall-to-roof connection will have to transmit the loads (tensile as well as compressive) from the roof to the concrete wall. Because of the gas enclosed under the roof, this connection will moreover have to be vapour-tight.

The fulfillment of these two requirements calls for a strong and, in fact, also a rigid connection of the concrete wall to the steel roof. In addition, however, the connection will have to allow the deformations to take place which are caused by solar radiation acting on the roof, cooling in the cold season, varying gas pressure in the tank, etc. These deformations may be quite large and may thus give rise to regularly recurring movements of the roof in relation to
the wall. These movements may in turn cause fatigue phenomena in the steel roof, more particularly at its connection with the wall.

In view of the requirements to be fulfilled, considerable care should be devoted to detailing the connection between the concrete wall and the steel roof. The vapour-tightness of the connection is also important.

Fig. 49. Example of a connection of a concrete wall to a steel roof

6.4.3 Connection of concrete wall to concrete roof

A concrete wall has to undergo various deformations (see 6.2.1). These cannot be neglected in a case where a concrete tank is pro-
vided with a concrete roof structure, for a rigid wall-to-roof connection can give rise to large meridian moments in the wall. For this reason the vertical prestress in the wall should be continued into this connection. The latter can thus be designed as a rigid connection (fig. 50a), with its principal advantage that no differential deformation occurs between wall and roof at this connection, so that continuing any insulating layers, etc. on the inside of the structure across this connection presents few problems.

The wall-to-roof connection may, however, be designed as a hinged connection (fig. 50b), the principal advantage of which is that the meridian moments are now greatly reduced, as the roof can undergo deformation in relation to the wall. However, in this case the continuation of insulating layers, etc. on the inside across the connection does present more problems.

Fig. 50a. Rigid wall-to-roof connection

Fig. 50b. Hinged wall-to-roof connection
6.4.4 Pipes through a concrete roof

Since the concrete roof does not have to perform a liquid-retaining function, apertures for the passage of pipes, for inspection purposes, etc. are allowed to be formed in it. As a rule, special steel structures (so-called pipe bridges) mounted on and in the roof are used to support such pipes.

If pipes are installed on the roof structure, they may leak, thus posing the hazard of local temperature shock affecting the concrete structure. This possible effect must be taken into account in the structural design of the concrete roof. Among the deciding factors with regard to this hazard are the severity of the spill (i.e., the equantity of liquid that is liable to leak out of pipeline in a short time), the area over which this liquid may spread, and the length of time for which the concrete structure is in contact with the cold liquid.

6.5 Functions of coatings and insulating layers attached to concrete structures

The concrete storage tanks described here should be provided with coatings and insulating layers within the structure or on the surface thereof in such a manner that they are:

(a) under normal service conditions: liquid-tight
gas-tight
vapour-tight

(b) in the event of disasters: liquid-tight and not giving rise to severe evolution of gas resulting from direct contact of the cold liquid with the concrete wall.

It has been explained in Chapter 3 that concrete is not be regarded as completely gas-tight and vapour-tight and that, partly on account of its relatively large structural thickness, it moreover has a high thermal capacity. This means that extra arrangements are needed to
ensure that the concrete structure fulfils the above-mentioned requirements.

6.5.1 Gas-tightness

In many cases the space inside the concrete structure is filled with gas. This gas may derive from the liquid because this space is in open communication with the space directly over the liquid or because some leakage occurs through the actual liquid-retaining wall. Alternatively, this gas may be of a different kind from the gas stored in the tank: thus it may more particularly be a gas introduced for inertizing the space within the structure, but outside the actual liquid-containing vessel.

In either case the gas in the above-mentioned spaces is under some (excess) pressure. Hence a certain quantity of such gas will be able to penetrate through a concrete wall not provided with a coating or similar layer. Although the actual quantity of gas thus escaping is relatively very small, it is nevertheless desirable to prevent any gas flow through the wall. To ensure this, a gas-tight coating or similar arrangement on the inner face of the concrete wall or a steel liner be installed in it will provide a suitable solution.

6.5.2 Vapour-tightness

The water vapour pressure in the spaces inside the concrete structure will in many cases be substantially lower than that in the external atmosphere.

In the zone just inside the concrete wall the vapour pressure will be determined by the lowest temperature occurring in the spaces communicating with that zone (e.g., the cavities within the perlite insulation close to a steel inner tank, CIS system). As a result, water vapour from the atmosphere will strive to penetrate inwards through the concrete wall. The presence of this vapour is particularly unfavourable to the proper functioning of the insulating
system because it will condense at low temperatures and indeed, below 0 °C, be likely to cause ice formation.

Besides the ingress of atmospheric water vapour, the free water (still) present in the concrete must be reckoned with, though the quantity of such water is of course limited.

It is evident that the penetration of moisture into the space on the inside of the outer wall is something to be prevented. This can be achieved by:

(a) the application of a vapour-tight coating on the outside of the structure;
(b) the application of a vapour-tight coating on the inside of the structure;
(c) the installation of a steel liner in the concrete wall.

6.5.3 Vapour-tight coating on the outside

This coating cannot in fact be applied until the tank has been cooled down to its service temperature. The reason is that, prior to the commissioning of the tank, water vapour will - under certain weather conditions - tend to make its way to the exterior of the tank. This movement of moisture in the wall will develop pressure behind the coating and may thus detach it from the outside face. Such a coating will often be of a fairly simple type and not able to resist the vapour pressure that thus builds up behind it.

6.5.4 Gas- and vapour-tight coating on the inside

This coating should be intimately connected to the concrete over its entire surface so as to seal off the concrete as completely as possible. Furthermore, the connection of the coating to the concrete should be able to resist tensile stresses if any cavities locally occur between the coating and the concrete. In the absence of adequate tensile resistance of the coating, "blistering" thereof could occur in consequence of progressive condensation in such cavities.
For this reason, but also in order to limit the temperature gradient in the concrete wall, it is advisable so to design the insulation interposed between the liquid and the concrete wall that the temperature at the inner face of the concrete remains well above 0 °C. If this temperature were below zero, possible condensation between the concrete and the coating could result in the formation of ice lenses. This phenomenon would exert large forces tending to destroy the connection of the coating to the concrete.

Since steel liners can never be really intimately connected to the concrete surface, they can be used in lieu of the coatings envisaged here only if the drawbacks associated with liners are duly realized by the designer and are - in any particular case - not considered to be of decisive importance.

6.5.5 **Steel liner incorporated in the concrete structure**

If steel liners are installed in the concrete (wall) structure, they can very effectively prevent moisture from penetrating into the space behind the wall. The liners should be interconnected by gas-tight weld seams between the plates.

6.5.6 **Insulating layers structurally connected to the inside of a concrete structure**

In the case of concrete structures for liquid gas storage which are located between the cooled storage space and the atmosphere it is usually necessary to insulate such structures externally, using layers of a material which possesses adequate strength, i.e., is able to transmit forces.

Such insulating layers are necessary in the following circumstances:

(1) If, in the event of a disaster of leakage of the inner tank, cold liquid impinges on the outer wall and then - on coming into direct contact with the "warm" concrete wall - undergoes intensive evaporation (example: CIS, C--IS, C--SIS).
(2) If the inner tank structure itself does not resist the liquid pressure, but transmits it direct — via the insulation layers — to the outer tank, in which case it is likewise necessary to reckon with possible leakage of the inner tank (example: CIL).

(3) If the concrete wall is monolithically connected to the base of the tank in such a manner that no deformation of wall and base in relation to each other can occur. In that case the cooling that the concrete wall may undergo — even in consequence of a disaster with outflow of liquid — must be restricted in order not to overstress the wall-to-base connection.

If they come into contact with the cold liquid or are otherwise subjected to low temperatures, the above-mentioned insulating layers will tend to shorten by contraction. In order to ensure that these layers will function properly under all conditions, they should:

(a) be so attached to the concrete wall that cooling will not cause any gap or cavity to form between the insulation and the wall (otherwise liquid can get into such cavities if the insulation cracks or tears);

(b) be of such construction that — in the event of a large temperature difference in the insulation — they will not develop continuous (through-and-through) cracking that would enable the liquid to reach the concrete wall (see also point a);

(In this respect it must be borne in mind that some degree of porosity of the insulation or the local occurrence of micro-cracking in it will not be objectionable, as the pores and local micro-cracks (temperature gradient in the insulation!) will contain gas which cannot flow and will therefore not cause any extra evaporation of liquid).

(c) be of such quality that they can transmit compressive forces (due to the liquid) to the concrete wall.
These insulating layers must accordingly fulfil requirements with regard to:

(a) compressive strength: at low temperatures;
(b) tensile strength: at low temperatures, both in the vertical and the horizontal direction;
(c) liquid-tightness: complete;
(d) gas-tightness: to a limited extent.

From (b), (c) and (d) it follows that at low temperatures a limited amount of purely local micro-cracking is permissible. In this respect a low value of the modulus of elasticity, in combination with a high tensile strength, is important.

Insulating layers built up of block-type elements will have to be assembled in such a way that the joints can transmit tensile forces both in the horizontal and in the vertical direction. For all insulating layers it is essential to bestow much care on the detailing of the connection of the insulation to the concrete structure wherever discontinuities occur (at wall-to-base and wall-to-roof junctions). The tensile forces set up in the insulation as a result of cooling will have to be resisted here and be transmitted to the wall, so as to ensure that the insulation cannot undergo vertical and/or horizontal displacement in relation to the wall and thus become detached from it.

In practice, various systems have been developed for the insulating layers envisaged here. The designer will have to assess the available systems with regard to the whole complex of requirements applicable to the insulation. Such assessment is outside the scope of this report.

6.5.7 Summary

Vapour-tightness of the concrete tank wall

1. vapour-tight layer on the outside; mostly a simple texture;
2. steel liner in the wall;
3. vapour-tight layer on the inside, intimately connected to the concrete, combined with insulating layers, usually connected to the wall.
Gas-tightness of the concrete tank wall

Outer concrete wall which may, on its inner face, come into direct contact with cold liquid (does not apply to a concrete inner tank)

1. gas-tight layer on the inside;
2. steel liner in the wall.

insulating layers, structurally connected to the concrete wall.
Peak-shaving plant - Maasvlakte - Nederlandse Gasunie - Rotterdam Europort
Installation tower for pipes
Made with prefabricated concrete elements
Information page 232
GUIDELINES FOR TECHNICAL OPERATING REQUIREMENTS

In the design of structures for "unpressurized cooled storage", whether of steel or of concrete, assumptions are made with regard to the structure when in use and to putting it into, and taking it out of, service. The inspections and checks which have to be performed during these operational phases are more particularly of importance in this context.

In view of the relationship between design and use of the structure, it is advisable to formulate a number of technical operating requirements. Obviously, the requirements laid down by the user must be duly taken into account. In accordance with the scope of this report, the requirements formulated in the present chapter relate only to concrete structures.

7 Inspections and checks when the structure is in service

7.1 Wall structures

Various forms of construction in concrete are possible for "unpressurized cooled storage" (see Chapter 4). From among these various possibilities the designer can make a choice, depending on the nature of the liquefied cooled gas, the safety requirements with regard to internal and external influences, etc.

The concrete walls embodied in the forms of construction in concrete constitute the inner tank or the single-walled tank ($C_{LIC_L}$, $SIC_L$, $CIL$ and $C--CIL$), the outer tank ($CIS$ and $C_{LIC_L}$) or the safety wall ($C--SIS$, $C--IS$, $C--S$ and $C--CIL$).

If the concrete wall functions as the second liquid-retaining wall (safety wall or outer tank), it will not be subjected to liquid pressure and temperature loading under normal conditions of service. For a wall of this kind it will therefore suffice to perform an annual visual inspection. The concrete safety wall or outer tank will then in any case be inspected externally.
Most safety walls (C--SIS, C--IS and C--CIL) are also accessible for inspection on the inside. For safe access to the gap it will, however, be necessary to take certain precautions (see 7.1.2), arrangements for which can already be made at the design stage (e.g., by making the gap suitably wide and providing openings in the wall).

In the Netherlands there are no special regulations or guidelines for the inspection of concrete structures under service conditions — presumably because there is not very much need for this. It is essential, however, that such an inspection is carried out systematically. For this purpose the ACI Committee 201 has compiled a check list with accompanying definitions, though admittedly it is not so much concerned with the specific aspects of concrete storage tanks and safety walls [1-21]. The systematic approach embodied in the check list could certainly be adopted, however.

The inspection should pay particular attention to the presence of small rust stains. These may be caused by the rusting of tie wire, nails, etc. which may have fallen into the formwork during construction. On the other hand, they may also occur in areas where, as a result of negligent workmanship, the concrete cover to the reinforcement is inadequate. If so, it is advisable to carry out repairs to such areas at the earliest possible opportunity, as this will be to the advantage of the durability of the concrete structure as a whole.

In view of the above-mentioned causes of rust stains at the concrete surface it is evident that these "defects" can be prevented by careful execution of the concreting work. Such care is essential, anyway, in order to obtain a high-quality concrete structure. If this condition is satisfied, it will be found that with concrete as the construction material a "maintenance-free" structure will have been obtained.

If the concrete wall forms the "primary tank" (inner tank of single-walled tank), in the CIL and C--CIL systems the outside of that wall
can be inspected in the manner described in the foregoing. (In the C--CIL system the gap will not hamper the inspection, if appropriate arrangements are made, such as constructing a gap of generous width and providing openings in the wall).

On the other hand, in the CLICL and SICL systems the outside of the wall is covered by insulation, etc. and therefore not accessible to visual inspection. In this respect there is much similarity with the inner tank of a double-walled steel tank. Actually, such walls can be inspected only when the tank is out of service, but their behaviour will already have been observed on earlier occasions, namely, during the loading tests ("water test" and "gas test") and on commissioning the tank, i.e., putting it into service ("cooling test", more particularly the "cooldown operation").

Besides, concrete walls have the great advantage that thermocouples can be incorporated in them during construction. With the aid of these measuring devices the temperature distribution and behaviour in these walls can be monitored during cooldown and while the tank is in service. In this way any leakage can be detected, while the performance of the insulation can also be checked.

Incidentally, the durability of concrete walls for "primary tanks" will present no problems, provided that such walls are well designed and well constructed [1-25].

If a concrete wall is internally insulated, it is possible to verify on the outside of this wall whether the insulation is functioning satisfactorily. At any rate, this is true of the CIS, CLICL, CIL and C--CIL systems, in which the insulation has to function when the tank is in normal use. (In the C--S system it will have to do this only in the event of leakage or failure of the inner tank).

If local condensation or ice formation ("cold spots") is observed on the outside of the concrete wall, it indicates that the insulation is not functioning properly in the areas concerned. In such cases remedial action to repair the insulation will have to be taken.
Checking the insulation will, however, have to be done first of all at the time of test loading the tank, more particularly during the "cooling test" ("cooldown operation"), when the above-mentioned thermocouples can provide useful information. With a well-thought-out testing scheme it will in general be quite possible to detect in good time any weak spots that may exist in the insulation, so that they can be repaired.

7.1.2 Gaps - Annular spaces

In the C--SIS, C--IS and CI--S systems, a steel tank (single-walled or double-walled) is enclosed within a concrete safety wall. The outside of such a steel tank, or its insulation, will have to be regularly inspected, just as the outside of a steel tank not surrounded by a safety wall.

This inspection will be done from within the gap between the steel tank and the safety wall, but cannot permissibly be carried out until it has been established with certainty that there is no "critical" gas/air mixture in the gap.

To ensure this, a gas detection system must be installed in the gap. If a certain threshold value is exceeded, or as a precautionary measure in advance, the gap is filled with an inert gas which is heavier than the combustible gas that may be in the gap ("inertization"). In this way the formation of a "critical" gas/air mixture can be prevented.

Another possible precaution is to ventilate the gap, more particularly by forced-draught - i.e., mechanical - ventilation. In a wide gap, however, natural ventilation may suffice for the purpose as practice has shown.

Before any persons are allowed to enter the gap it will moreover have to be ascertained that it is free from gases or reaction products that may be dangerous or harmful to human beings.

A gap should also be checked for the pressure of water. Any water that may have got in should be removed at once, through manholes
with valves, provided for the purpose in the bottom of gap or at the foot of the safety wall. These valves should be made of materials which can withstand low temperatures, so that they will not become defective and allow liquid to leak through in the event of leakage or failure of the storage tank.

A similar check will have to be carried out if the gap is provided with a sump from which the water is pumped away through a pipe over the top of the safety wall.

The arrangements for keeping the gap empty should regularly be checked for satisfactory functioning. In the case of manholes, etc. in the bottom or wall it should be ascertained that they are closed and liquid-tight in readiness for service in the event of leakage or failure of the storage tank.

### 7.1.3 Roofs and wall-to-roof connections

The roof structure and especially the wall-to-roof connection should be regularly inspected. In the case of steel roofs the inspection procedure is similar to that for steel storage tanks, while particular attention should be paid to the connection of the roof to the concrete wall, because here a rigid concrete structure is joined to a relatively flexible steel structure. This being so, varying gas pressure will often produce greater stress variations in such a connection than in the wall-to-roof connection of an all-steel or an all-concrete tank structure. It is therefore necessary to check regularly that no fatigue phenomena occur here, which are liable to cause leakage, for example.

### 7.1.4 Connections of pipes to tank roofs

It is not permissible, or at least very ill-advised, to have pipes going through the concrete walls of structures for "unpressurized cooled storage" (see 6.3.4). As a rule, therefore, all pipes will have to be routed via the roof. For supporting such pipes it is normal practice to install separate pipe bridges which are not
carried by the roof structure. With concrete roof structures, however, the pipes or pipe bridges may be supported directly on the roof, provided that the designer allows this in view of – among other considerations – the load capacity of the roof structure.

Pipe bridges will be subject to deformations, more particularly due to temperature variations. These deformations will, as a rule, differ from those of the roof structure, which are caused by loads as well as temperature variations. Hence the passages through the roof should be so constructed that any differences in deformation can be absorbed without adversely affecting the gas-tightness or insulation. Such passages should be regularly inspected with regard to this as well. Special monitoring equipment will often be required for the purpose.

7.1.5 Wall-to-base connections

The wall-to-base connection should be regularly inspected, particularly with a view to ascertaining that the constructional arrangements at the joint (if any) are still functioning properly and not disintegrating.

7.1.6 Base structures

If there is a ventilation and inspection space under the storage tank, as in the case of a concrete tank on piles, the underside of the base structure should be regularly inspected. For this purpose the same criteria can be applied as those for the inspection of wall structures (see 7.1.1). If sliding bearings have been installed between the base slab and the heads of the piles or columns, these bearings should likewise be inspected at regular intervals.

7.2. Commissioning and taking out of service

7.2.1 Commissioning

Commissioning a new storage tank, i.e., putting it into service, should be preceded by loading tests. For this purpose the "water test",
the "gas test" and the "cooling test" (which corresponds entirely to the normal "cooldown operation", see 5.8) can appropriately be applied.

During these loading tests the behaviour of the structure is closely observed. More particularly, attention is focused on the wall, roof and base structure, the liquid-tightness and gas-tightness of the tank, the functioning of the insulation, the behaviour of the connections (including the joints, if any), etc. A suitable program of testing, properly carried out, will provide a considerable degree of certainty that the structure as whole fulfils the requirements.

When a concrete tank is subjected to a "cooling test" or to the normal "cooldown operation", the temperature gradient that is set up in the wall will have to remain below the value adopted in the design or stipulated by the designer. This is monitored by means of continuous temperature measurements on the inside and outside of the tank. An even better idea of the temperature distribution can be obtained if the concrete wall is provided with thermocouples. The limit value envisaged above, which is not allowed to be exceeded, is so chosen that no cracking will occur in the concrete wall and in the connections during cooling. This condition of no cracking will then also be satisfied when the tank is in use.

During cooling, the concrete wall tends to undergo displacement in relation to the base. In most forms of construction in concrete the wall-to-base connection will therefore be designed to allow sliding or at least rotational (hinge action) movement. Such connections and, in particular, any joint associated with them should be observed during the cooling process.

If the concrete wall is internally insulated (as in the CIL and C--CIL systems), the temperature differences, and therefore the deformations, will be relatively small. In such cases the wall-to-base connection can suitably to be of the rigid type. Despite the relatively slight amount of cooling that such a concrete wall undergoes, temperature measurements on the inside and outside there-
of (and possibly also in the concrete itself) will have to be carried out in order to detect any irregularities.

In all cases where control of deformations is required during cooling, the instructions issued by the designer must be carefully followed. More often than not, he will be directly involved in supervising the "cooldown operation".

### 7.2.2 Taking out of service (shutdown)

When a storage tank is taken out of service, the "heating-up" operation will have to be conducted in just as gradual and controlled a manner as the "cooldown" (see 7.2.1). During this operation, too, the connections, etc. should be kept under observation.

### 7.2.3 Observations and repairs during maintenance phase

After shutdown of a tank, maintenance work is not allowed to start until it has been ascertained that it is entirely free of gas. This criterion applies not only to the actual interior space of the tank, but also to the concrete wall and especially to the insulation (if any) on the inside thereof, for pockets of gas may remain in the insulating material. So before any persons are allowed to go down into the tank, it must be certain that they will be in no danger. This requires extremely careful detection.

Any repairs to the concrete wall, insulation, liner, etc. should be executed under effective expert supervision. Where possible, the liner should be examined with the aid of special apparatus and control methods developed for the purpose.

### 7.3 Operational requirements

No special operational requirements are applicable to concrete tanks. The same requirements as those laid down for steel tanks may be applied, bearing in mind, however, that a number of these are relevant only to steel and not to concrete tanks. Within the scope of this report only
the technical operating requirements already outlined (see 7.1 and 7.2) need be considered. For the sake of completeness, attention is drawn to the regulations and codes existing in other countries with regard to the "unpressurized cooled storage", more particularly of LNG [1-13a/b, 1-14 and 1-15].
Peak-shaving plant - Maasvlakte - Nederlandse Gasunie - Rotterdam Europort
Overall view of plant
Information page 232
This chapter gives an overall general description of the manner in which concrete tank walls and safety walls are built and prestressed (see 8.1). The consequences of the method of construction (see 8.1.3) and the construction of concrete roofs (see 8.1.4) will also be considered. Finally, a number of tank structures actually built (see 8.2) are reviewed, while further particulars of some of these are given separately (see 8.3).

8.1 Constructional and prestressing techniques

8.1.1 Methods of construction

Cylindrical concrete structures such as tank walls and safety walls can be built in three different ways:

a. cast in situ by the "climbing formwork" method;
b. cast in situ by the "sliding formwork" method (slipforming);
c. prefabricated construction by assembling precast concrete units.

a. In the so-called "climbing formwork" method, which is a discontinuous operation, the inner formwork of the concrete wall is lifted a distance of several metres when the concrete of the previous "lift" has sufficiently hardened. The formwork is then secured and adjusted in its new position. Next, the prestressing tendons and the reinforcing bars are installed, and the outer formwork is then erected and is strutted against the inner formwork. In the so-called wrapping method of prestressing, also called "merry go round" system, the steel liner to be incorporated in the concrete is generally utilized as the outer formwork, a procedure which in itself imposes special requirements with regard to design and execution of the work.

Freshly mixed concrete is placed in the space enclosed between the inner and the outer formwork and is compacted. After this concrete has sufficiently hardened, the sequence of operations described above is repeated. The rate of concreting progress will of course depend on the necessary waiting time for the concrete in each successive "lift" to harden.
The "climbing formwork" method of construction has the advantage that the whole procedure can be properly supervised and checked, including the operations of fixing the tendons and reinforcement.

The horizontal joints between the successive "lifts", i.e., the annular segments concreted at one time, may cause problems, however, as the liquid-tightness of these "construction joints" is liable to be less good than that of the rest of the concrete wall. For this reason, special arrangements to ensure proper tightness of these joints are essential. If a steel liner is incorporated in the concrete, this possibly deficient liquid-tightness of the concrete at the joints will not adversely affect the liquid-tightness of the wall as a whole.

b. In the so-called "sliding formwork" method, which is a continuous operation, sometimes called "slipforming", the formwork is steadily and uniformly pulled up, sliding along the face of the freshly placed and compacted concrete. This operation of continuously raising the formwork is carried out with the aid of jacking rods.

So long as concreting proceeds uninterruptedly (day and night), no construction joints will occur in the wall when this method is applied. The surface of the concrete will often show marks caused by the "sliding", but these are usually not considered objectionable. This continuous procedure requires careful supervision and checking, especially with regard to fixing the tendons and reinforcement, and these supervisory duties will likewise have to continue on a round-the-clock basis, with different shifts of personnel.

Generally speaking, the rate of progress achieved with "sliding formwork" is higher than with "climbing formwork".

c. A precast concrete wall is assembled from "prefabricated" units, i.e., concrete units or elements cast under factory conditions in a precasting works. When they have been assembled on the construction site, the joints between them have to be sealed. The
liners (if any) incorporated in the concrete wall will then also have to be joined together by welding. These jointing and welding operations usually constitute the most vulnerable part of this construction method.

The factory-made precast concrete units are usually prestressed in their longitudinal direction, i.e., corresponding to the vertical direction of the concrete wall. After erection (including the jointing and welding work), a horizontal prestress is usually applied in addition, e.g., by the wrapping method. The dimensions and weight of the units are, as a rule, limited by the transport and erection possibilities.

This method of construction is not so suitable for concrete walls to be built around existing or previously completed steel tanks already in use, for there is a hazard in that the steel structures are liable to be damaged if some mishap occurs in erecting the precast concrete units, e.g., in a high wind.

8.1.2 Prestressing systems

Cylindrical concrete walls, such as tank walls and safety walls, can be prestressed in three different ways:

a. with post-tensioned steel;
b. by the so-called wrapping method (actually also a form of post-tensioning, though using a different technique);
c. with pre-tensioned steel.

a. In "prestressing with post-tensioned steel" the tendons are accommodated in preformed ducts extending horizontally and vertically in the concrete wall. After the concrete has sufficiently hardened, the tendons are tensioned and then anchored under tension. The horizontal (circumferential) tendons mostly extend round part of the circumference (e.g., 120°, 180° or 240°) and overlap with one another. They are anchored in so-called anchor piers. When the tendons have been anchored, the ducts in which they are accommodated within the concrete are grouted. In this way the pre-
stressing steel is protected from corrosion, while bond with the surrounding concrete is established.

b. In the so-called wrapping method or "merry go round" method the vertical prestress is applied in the same way as in a, but the horizontal prestress is produced by wrapping the cylindrical tank wall with prestressing steel, in the form of a continuous wire, applied under tension. When the first layer of wire has been wound round the tank, a layer of fine-aggregate concrete ("gunite") is pneumatically sprayed on the wall so as to cover the steel. Then the second and possible further layers of prestressing steel wire are wrapped round the tank and likewise covered with sprayed concrete.

c. In "prestressing with pre-tensioned steel" the tendons are first tensioned and anchored, after which concrete is placed around them. When the concrete has sufficiently hardened, the anchorages are released, so that the prestress is transferred to the concrete by direct bond between it and the embedded tendons. This technique is, in principle, suitable only for precast concrete units manufactured in a precasting works. It is therefore not applicable to the horizontal (circumferential) prestressing of the tank wall.

8.1.3 Consequences of manner of execution

Openings could temporarily be left in the concrete wall for bringing materials, etc. into the tank. This practice deserves unqualified condemnation, however, because when these openings are subsequently closed, it is virtually impossible to seal the joints in such a way as to render them liquid-tight at high liquid pressure.

This being so, if the concrete wall has to be built first, all materials and components for structures to be erected inside this wall will either have to be lifted over the upper edge of the wall or be introduced into the interior through a temporary access under the wall foundation and through the base slab. This latter solution is possible, however, only in those cases where the subsoil conditions
and the type of foundation permit it. In the case of a double-walled tank comprising, for example, a concrete outer tank and a steel inner tank it may be practicable to build the two walls more or less simultaneously. An (outer) concrete wall may, alternatively, be built last, after all other structures within it have been completed. The consequences entailed by the manner of execution of the work as envisaged here should be given careful consideration before any particular form of construction is chosen. It would, however, be outside the scope of this report to go into the effects that the manner of execution has upon the design of the structure.

8.1.4 Constructing the concrete roof

A light steel roof is frequently utilized as permanent formwork for building a concrete roof over a tank. The steel roof is raised into position with the aid of air pressure underneath it or with hoisting appliances and then connected to the concrete wall. It can also function as a vapour-tight layer for the roof structure, thus providing an attractive solution. A thick and therefore heavy concrete roof may, if desired, be constructed in two or more layers, each subsequent layer being concreted after the preceding one has hardened and can thus carry load. In this way a substantial saving in the required amount of falsework and propping can be effected.

8.2 Review of projects executed

Table 8a lists the tank construction projects which, to the authors' knowledge, have been carried out in the Netherlands. Projects carried out in other countries are listed in Table 8b. The various forms of construction are indicated by the coding system explained in Chapter 4.
Table 8a. Summary of projects carried out in the Netherlands, using concrete

<table>
<thead>
<tr>
<th>owner</th>
<th>place</th>
<th>capacity</th>
<th>product</th>
<th>number</th>
<th>system</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSM</td>
<td>Geleen</td>
<td>10,000 - 40,000 m³</td>
<td>naptha</td>
<td>6</td>
<td>C--IS</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>8,500 m³</td>
<td>butane</td>
<td>1</td>
<td>C--IS</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>16,500 m³</td>
<td>ethene/ethylene</td>
<td>1</td>
<td>C--IS</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>7,000 m³</td>
<td>acrylonitrile (ACN)</td>
<td>1</td>
<td>C--IS</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>26,000 m³</td>
<td>propene/propylene</td>
<td>1</td>
<td>C--IS</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>25,000 m³</td>
<td>ammonia</td>
<td>1</td>
<td>C--IS</td>
</tr>
<tr>
<td>Gasunie</td>
<td>Maasvlakte</td>
<td>57,000 m³</td>
<td>liquid natural gas (LNG)</td>
<td>2</td>
<td>C--SIS</td>
</tr>
<tr>
<td>UKF/Albatros</td>
<td>Rotterdam</td>
<td>22,000 m³</td>
<td>ammonia</td>
<td>1</td>
<td>C--IS</td>
</tr>
<tr>
<td>EssoChem</td>
<td>Rotterdam</td>
<td>23,300 m³</td>
<td>ammonia</td>
<td>2</td>
<td>C--IS</td>
</tr>
<tr>
<td>ICI</td>
<td>Rotterdam</td>
<td>4,000 m³</td>
<td>propene/propylene</td>
<td>1</td>
<td>CI--IS spherical storage tank</td>
</tr>
<tr>
<td>Ned.Stikstof Mij.</td>
<td>Sluiskil</td>
<td>10,000 m³</td>
<td>ammonia</td>
<td>1</td>
<td>C--IS</td>
</tr>
<tr>
<td>Ned.Stikstof Mij.</td>
<td>Sluiskil</td>
<td>20,000 m³</td>
<td>ammonia</td>
<td>1</td>
<td>C--IS</td>
</tr>
<tr>
<td>year</td>
<td>place</td>
<td>owner</td>
<td>capacity (in m³)</td>
<td>product</td>
<td>description</td>
</tr>
<tr>
<td>------</td>
<td>-----------------</td>
<td>--------------------------------------------</td>
<td>------------------</td>
<td>------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1952</td>
<td>Chicago</td>
<td>Linde Comp., Div. of Union Carbide Corp.</td>
<td>1.000</td>
<td>liquid oxygen</td>
<td>double-walled concrete tank, without liners (prototype)</td>
</tr>
<tr>
<td>1953/54</td>
<td>Chicago</td>
<td>Linde's East Chicago, Indiana Plant</td>
<td>2.650</td>
<td>liquid oxygen</td>
<td>double-walled concrete tank, without liners</td>
</tr>
<tr>
<td>1962</td>
<td>Chicago</td>
<td>Institute of Gas Technology (IGT)</td>
<td>159</td>
<td>liquid natural gas</td>
<td>concrete tank with liner and isolation (experimental tank)</td>
</tr>
<tr>
<td>1969</td>
<td>Staten Island (New York)</td>
<td>Texas Eastern Transmission Comp.</td>
<td>95.000</td>
<td>liquid natural gas</td>
<td>concrete tank with aluminium liner</td>
</tr>
<tr>
<td>1972</td>
<td>Philadelphia (Penn.)</td>
<td>Philadelphia Electric Comp.</td>
<td>63.000</td>
<td>liquid natural gas</td>
<td>concrete safety wall (precast concrete units)</td>
</tr>
<tr>
<td>1973</td>
<td>Cape Cod (Mass.)</td>
<td>Buzzards Bay Gas Comp.</td>
<td>8.700</td>
<td>liquid natural gas</td>
<td>concrete tank with steel liner</td>
</tr>
<tr>
<td>1974</td>
<td>Philadelphia Works</td>
<td>Philadelphia Gas Works</td>
<td>92.500 (2x)</td>
<td>liquid natural gas</td>
<td>double-walled concrete tank (3 m of concrete between inner and outer tank)</td>
</tr>
<tr>
<td>Year</td>
<td>Place</td>
<td>Owner</td>
<td>Capacity</td>
<td>Product</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
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<td>----------</td>
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</tr>
<tr>
<td>1975</td>
<td>Winnipeg</td>
<td>Greater Winnipeg Gas Comp.</td>
<td>40,000</td>
<td>Liquid petroleum gas</td>
<td>Concrete tank with steel liner</td>
</tr>
<tr>
<td>1971/1972</td>
<td>Stuttgart</td>
<td>Technische Werke Stuttgart</td>
<td>30,000</td>
<td>Liquid natural gas</td>
<td>Concrete outer tank, with earth backfill, heated base and wall</td>
</tr>
<tr>
<td>1972</td>
<td>Neurenberg</td>
<td>ICI</td>
<td>1,600</td>
<td>Liquid nitrogen</td>
<td>Concrete tank with steel membrane</td>
</tr>
<tr>
<td>1974</td>
<td>Billingham (Durham)</td>
<td>ICI</td>
<td>18,000 (3x)</td>
<td>Liquid ammonia</td>
<td>Concrete safety wall</td>
</tr>
<tr>
<td>1974</td>
<td>Belfast (Ulster)</td>
<td>Richardson Fertilizers (ICI)</td>
<td>4,500</td>
<td>Liquid ammonia</td>
<td>Concrete safety wall</td>
</tr>
<tr>
<td>1976</td>
<td>Partinton-Manchester (Cheshire)</td>
<td>British Gas</td>
<td>69,250</td>
<td>Liquid natural gas</td>
<td>Concrete safety wall</td>
</tr>
<tr>
<td>1976</td>
<td>Avonmouth-Bristol (Gloucester)</td>
<td>British Gas</td>
<td>58,900</td>
<td>Liquid natural gas</td>
<td>Concrete safety wall</td>
</tr>
<tr>
<td>1977</td>
<td>Seal Sands</td>
<td>Monsanto</td>
<td>18,000</td>
<td>Liquid ammonia</td>
<td>Concrete safety wall</td>
</tr>
<tr>
<td>1977</td>
<td>Billingham (Durham)</td>
<td>ICI</td>
<td>14,000</td>
<td>Liquid ethene (ethylene)</td>
<td>Concrete safety wall</td>
</tr>
<tr>
<td>year</td>
<td>place</td>
<td>owner</td>
<td>capacity</td>
<td>product</td>
<td>description</td>
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<td>--------------------------------------------------</td>
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<tr>
<td></td>
<td>BRITAIN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>Avonmouth-Bristol</td>
<td>British Gas</td>
<td>58,900</td>
<td>liquid natural gas</td>
<td>concrete safety wall</td>
</tr>
<tr>
<td></td>
<td>(Gloucester)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FRANCE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1965</td>
<td>Nantes</td>
<td>Gaz de France</td>
<td>2,000</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane (experimental tank)</td>
</tr>
<tr>
<td></td>
<td>(1967/1968)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>Fos-sur-Mer</td>
<td>Gaz de France</td>
<td>80,000</td>
<td>liquid natural gas</td>
<td>concrete outer tank with steel membrane</td>
</tr>
<tr>
<td>1978</td>
<td>Montoir-en-Bretagne</td>
<td>Gaz de France</td>
<td>120,000</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2x)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>IRELAND</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1975</td>
<td>Cork</td>
<td>Nitrigen Eirean Teoranta</td>
<td>18,000</td>
<td>liquid propane</td>
<td>concrete safety wall</td>
</tr>
<tr>
<td>1975</td>
<td>Cork</td>
<td>Nitrigen Eirean Teoranta</td>
<td>18,000</td>
<td>liquid ammonia</td>
<td>concrete safety wall</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ITALY</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>(plan) Panigaglia</td>
<td>SNAM/ENI</td>
<td>50,000</td>
<td>liquid natural gas</td>
<td>(plan) concrete safety wall around steel tank dating from 1965</td>
</tr>
<tr>
<td></td>
<td>(2x)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>(plan) Monfalcone</td>
<td>SNAM/ENI</td>
<td>130,000</td>
<td>liquid natural gas</td>
<td>(plan) double-walled concrete tank</td>
</tr>
<tr>
<td></td>
<td>(2x)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 8b. Summary of projects carried out in other countries, using concrete

<table>
<thead>
<tr>
<th>year</th>
<th>place</th>
<th>owner</th>
<th>capacity (in m³)</th>
<th>product</th>
<th>description</th>
<th>system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>Negishi (Yokohama-Tokyo)</td>
<td>Tokyo Gas Comp.</td>
<td>10.000</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane</td>
<td>CIL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tokyo Electric Power Comp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1972</td>
<td>Negishi (Yokohama-Tokyo)</td>
<td>Tokyo Gas Comp.</td>
<td>60.000</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane</td>
<td>CIL</td>
</tr>
<tr>
<td>1974</td>
<td>Sodegaura (Chiba-Tokyo)</td>
<td>Tokyo Gas Comp.</td>
<td>60.000 (2x)</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane</td>
<td>CIL</td>
</tr>
<tr>
<td>1975</td>
<td>Semboku I Osaka</td>
<td>Osaka Gas Comp.</td>
<td>45.000</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane</td>
<td>CIL</td>
</tr>
<tr>
<td>1975</td>
<td>Nanao (Ishikawa)</td>
<td>Bridgestone Liquefied Gas Comp.</td>
<td>51.500 (2x)</td>
<td>liquid petroleum gas</td>
<td>concrete tank with steel membrane</td>
<td>CIL</td>
</tr>
<tr>
<td>1976</td>
<td>Sodegaura (Chiba-Tokyo)</td>
<td>Tokyo Electric Power Comp.</td>
<td>60.000 (3x)</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane</td>
<td>CIL</td>
</tr>
<tr>
<td>1976</td>
<td>Sodegaura (Chiba-Tokyo)</td>
<td>Tokyo Gas Comp.</td>
<td>60.000</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane</td>
<td>CIL</td>
</tr>
<tr>
<td>1977</td>
<td>Negishi (Yokohama-Tokyo)</td>
<td>Tokyo Gas Comp.</td>
<td>95.000</td>
<td>liquid natural gas</td>
<td>concrete tank with steel liner</td>
<td>CIL</td>
</tr>
<tr>
<td>1977/78</td>
<td>Sodegaura (Chiba-Tokyo)</td>
<td>Tokyo Electric Power Comp.</td>
<td>60.000 (3x)</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane</td>
<td>CIL</td>
</tr>
<tr>
<td>1978</td>
<td>Negishi (Yokohama-Tokyo)</td>
<td>Tokyo Gas Comp</td>
<td>95.000</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane</td>
<td>CIL</td>
</tr>
</tbody>
</table>
Table 8b. Summary of projects carried out in other countries, using concrete

<table>
<thead>
<tr>
<th>year</th>
<th>place (only underground tanks)</th>
<th>owner</th>
<th>capacity (in m³)</th>
<th>product</th>
<th>description</th>
<th>system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978</td>
<td>Sodegaura (Chiba-Tokyo)</td>
<td>Tokyo Electric Power Comp.</td>
<td>60.000 (2x)</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane</td>
<td>CIL</td>
</tr>
<tr>
<td>1979</td>
<td>Sodegaura (Chiba-Tokyo)</td>
<td>Tokyo Gas Comp.</td>
<td>62.000</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane</td>
<td>CIL</td>
</tr>
<tr>
<td>1979</td>
<td>Sodegaura (Chiba-Tokyo)</td>
<td>Tokyo Gas Comp.</td>
<td>58.000</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane</td>
<td>CIL</td>
</tr>
<tr>
<td>1979/1980</td>
<td>Negishi (Yokohama-Tokyo)</td>
<td>Tokyo Gas Comp.</td>
<td>95.000</td>
<td>liquid natural gas</td>
<td>concrete tank with steel membrane</td>
<td>CIL</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>place</th>
<th>capacity</th>
<th>product</th>
<th>description</th>
<th>system</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPAIN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1969</td>
<td>Barcelona</td>
<td>Gas Natural (now: ENAGAS)</td>
<td>40.000 (2x)</td>
<td>liquid natural gas</td>
</tr>
<tr>
<td>1979</td>
<td>Barcelona</td>
<td>ENAGAS</td>
<td>80.000</td>
<td>liquid natural gas</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>place</th>
<th>capacity</th>
<th>product</th>
<th>description</th>
<th>system</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOUTH AFRICA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1972</td>
<td>Sasolburg</td>
<td></td>
<td>12.300</td>
<td>liquid ethene (ethylene)</td>
</tr>
</tbody>
</table>


8.3 **Particulars of some projects executed**

**Staten Island, New York:** two LNG tanks

system: $C_L^{IC_L}$ (double-walled concrete tank, with 3 m of concrete between inner and outer tank)

- base slab resting on subsoil
- steel roof structure
- capacity: 143,000 m$^3$ (900,000 barrels)
- external diameter of outer tank: 84 m
- external diameter of inner tank: 74 m
- height of wall: 36 m
- wall thickness at top: 0.18 m
- wall thickness at foot: 0.46 m

both walls constructed of precast concrete units (prestressed with pre-tensioned steel); horizontal prestress applied by wrapping method after erection of units

- base structure: reinforced concrete slab, 0.8 m thick, directly on subsoil

ref. [8-6]
Fos-sur-Mer, France: one LNG tank

system: CIS (concrete outer tank with steel "membrane", around steel inner tank)

base slab raised clear of subsoil
pile foundation
concrete roof

capacity: 80,000 m$^3$
internal diameter of concrete tank: 55.8 m
height of concrete tank: 39.9 m
thickness of concrete roof: 0.3 m
thickness of tank wall: 0.9 m
thickness of base: 0.8 m

wall prestressed with internal tendons (Freyssinet system)

ref. [6-20 and 8-10]

Montoir-en-Bretagne, France: two LNG tanks

system: CIL (concrete tank with steel "membrane")

base slab raised clear of subsoil (2 m)
pile foundation
concrete roof on steel dome

capacity: 120,000 m$^3$
internal diameter of concrete wall: 63.1 m
height of concrete wall: 43.5 m
thickness of concrete roof: 0.6 m
thickness of tank wall: 0.9 m
thickness of base: 1.0 m

wall prestressed with internal tendons (Freyssinet system)

ref. [8-9 and 8-18]
Maasvlakte, Netherlands: two LNG tanks

system: C--SIS (double-walled steel tank with concrete safety wall)

steel tanks:
external diameter: 50.20 m
height: 31.20 m
capacity: 57,000 m³
steel roof structure

base structure:
reinforced concrete slab, 0.8 m thick, on piles

safety walls:
prestressed concrete, 0.40 m thick

external diameter: 55.40 m
height: 33.0 m

tank wall prestressed with tendons in grouted ducts - Two systems:
Freyssinet (hor.) and Dywidag (vert.)

ref. [8-1, 8-2 and 8-3]
CONCLUDING REMARKS

This report is concerned with the possibilities of concrete as a construction material for the storage of liquefied cooled hydrocarbons and similar substances. It endeavours to present as a clear a picture as possible of what the concrete storage vessel can offer.

A perusal of the text will have shown that it no more than briefly outlines the fundamentals on which a pronouncement as to the - economic - reality of concrete for such storage can be based.

These fundamental points are largely dependent on the loads for which the structure in question has to be designed, with due regard to certain load factors. It is precisely the problem of indicating the magnitude of these loads that is so difficult. The magnitude, more particularly of the so-called special loads, depends on many factors, including the following:

- the nature of the product to be stored;
- the quantity of the product to be stored;
- the nature of the installation of which the tank forms part;
- the geographical location of the storage facilities (in relation to other installations, populated areas, etc.);
- the construction of the tanks ("flexible" tank structures absorb and transmit loads differently from "rigid" ones).

Those determinative special loads will vary from case to another. Hence it is virtually impossible to indicate their magnitude in general terms. The same is true of the values to be adopted for the load factors.

Yet the only realistic approach to answering the question as to what form of construction should be employed will have to be based on weighing the economic aspects against one another, with reference to given boundary conditions.

Because of the absence of a well-defined condition on the basis of which these boundary conditions can in turn be established, the
approach often takes the form of asking "to state what special loads a particular structure can support, so that those special loads can then be included as important criteria in the overall package of requirements with which the design is expected to comply".

It is this very approach that creates a situation where the various structural possibilities - more particularly in steel and in concrete respectively - are placed in confrontation with one another. As a result, these possibilities - including those comprising combinations of steel and concrete, as well as various industrial developments - tend to become locked in a process of "trying to outbid" one another. This situation, which repeatedly threatens to develop, has been mentioned here in order to show clearly that the above-mentioned approach is not the right one and may even give rise to undesirable polarization between different forms of construction.

In this report it has been endeavoured to avoid the above-mentioned problems by presenting as clearly as possible what solutions concrete structures can offer, and why, as well as explaining what properties of these structures are relevant with regard to this. Where, by way of exception, steel tanks are discussed, this has not been done with a view to contrasting steel with concrete, but in order to indicate what special conditions concrete structures may have to cope with.

By virtue of the wide range of shapes and dimensions available to the concrete designer, he has at his disposal a number of possibilities from which to choose in providing structures for the storage of "hazardous" substances as safely as possible. To indicate these possibilities with the backing of clear information on their respective advantages and disadvantages is one of the objectives of this report.

Since its subject-matter comprises developments which have hardly yet begun, but of which much can be expected in the future, it will be necessary to judge every solution with reference to all the significant aspects. If information is lacking or inadequate for the purpose, it will be necessary to obtain, by means of purpose-directed research, a better basis for the assessment of a design. In this re-
spect, too, the report should be regarded as a review of the "state of the art", i.e., as a document taking stock of the present position and liable to be rendered obsolete as time goes by.

Closely bound up with the storage of hazardous substances is the transport of these substances, both from the means of conveyance to the tank (and vice versa) and from the place of production to the place of consumption. Various risks which must not be underrated attend these transport operations. The present report does not cover those aspects. However, in order to direct the reader's attention to potential developments in that direction, a list of literature references relating to the use of concrete in floating structures is given on page 237.

In conclusion it can be stated that, in weighing the possibilities that concrete structures offer with regard to the safe storage of liquefied cooled hydrocarbons, etc., it is important to know the relevant properties of these structures. On the basis of the given boundary conditions it can then be decided whether these possibilities are economically realistic options. The aim of publishing this report was to make a contribution to arriving at such a decision.
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