Nine per cent nickel–
28 years of reliable service
in liquefied natural gas containment

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ABSTRACT

A five-year multinational study sponsored by the Gas Research Institute (GRI) has shown in quantitative terms that 9% nickel steel has very high resistance to the initiation and propagation of brittle fracture at liquid natural gas (LNG) temperatures.

It has established the validity of laboratory-scale tests for determining the ability of the steel to stop large running cracks that might be generated by major external accidents. It provides reassurance that steels made by current modern steelmaking practices will meet the desired leak-before-failure criteria in LNG service and at even lower cryogenic temperatures.

This publication reviews the practical significance of the GRI studies to the designers and owners of liquefied natural gas facilities, and relates them to the unblemished record that the steel has compiled since the early 1960s in ship and storage tanks.

A further history of reliable cryogenic performance in facilities for handling liquid oxygen, nitrogen, argon and helium is discussed.

An extensive bibliography of key references is appended.

INTRODUCTION

The research leading to the development of nine per cent nickel steel was started in the early 1940s in the United States by The International Nickel Co.[1]

It recognized the need for an economical high-strength alloy steel with a level of toughness at cryogenic temperatures required for the design and safe operation of large-scale plant for producing and storing liquid industrial gases such as oxygen, nitrogen and argon.

At that time, studies were under way as to the feasability of transporting and storing natural gas in the liquefied form. It was clear that the realization of such new technologies would be greatly aided by the availability of a material that could be adaptable to designs, fabricating practices and regulatory systems that had been evolved for large-scale, high-performance process equipment in the petroleum, chemical and power industries.

A primary consideration in the research was to be assured that any new steel would avoid the onset of brittleness at subzero temperatures, a characteristic of ordinary structural steels. The mechanisms by which such brittleness occurred, the means of measuring it, and the ways to prevent it were only dimly understood at the time[2], and it remained for the classic investigations of ship fractures in the early 1950s[7] to lay the basis for *fracture mechanics* by which today the initiation, propagation, and arrest of brittle fracture in large structures can be predicted and prevented.

Part I
The Application of Nine Per Cent Nickel Steel For Cryogenic Equipment

When the research that resulted in 9Ni steel was presented in 1947,[3,4] its cryogenic toughness was evaluated by the Charpy impact test in liquid nitrogen at -196°C (-320°F), and related to the 20J (15 ft. lb.) minimum required in the American Society of Mechanical Engineers (ASME) Boiler Code for pressure vessel steels for other cryogenic applications. Realizing the limitations of the Charpy test of small laboratory specimens to predict behaviour in large fabricated structures, in 1948 a series of destructive tests was performed on small simulated pressure vessels by impacting them when filled with liquid nitrogen.[5]

The success of these tests led in 1952 to an American Society for Testing and Materials (ASTM) specification and ASME approval for the use of double normalized and tempered 9Ni steel for shop-fabricated and stress relieved cryogenic vessels.

By 1960, several hundred vessels had been built for storing liquid oxygen and nitrogen *(Fig. F)*. Meanwhile, by the late 1950s the schemes for large-scale LNG operations had advanced to the construction of prototype facilities in the United Kingdon, France and the U.S.A. The properties and long-term behaviour of 9Ni continued to be studied, particularly as it might be utilized in LNG service.[6,8,9,10] In October, 1960 *Operation Cryogenics* was conducted in the U.S. before representatives of major code and specification bodies.[11]

Nine large cylindrical and rectangular vessels were tested to destruction in liquid nitrogen to provide the evidence that 9Ni vessels, fabricated by field erection practices and put into service without stress relief, would have great resistance to over-stress, and would retain toughness at liquid nitrogen temperatures, *(see insert and Figs. H).* Based on the results of this demonstration, ASME special Code Case 1308-4 was issued in May, 1963, setting allowable design stresses for both quenched and tempered, and double normalized and tempered plates, and permitting the use of 9Ni steel in the as-welded condition.[12]

Similar vessel tests were conducted in Italy in July, 1964[14] and in Japan the same year. As a consequence, 9Ni steel was eventually recognized as suitable for LNG service by ASME, American Petroleum Institute, American Bureau of Ships, Lloyd's Register of Shipping, The U.S. Coast Guard, Bureau Veritas, Norske Veritas, Technischer Uberwachsen Verein, ANCC, and Registro Italiano Navale.

As early as 1952, 9Ni steel had been used for shop-fabricated pressure vessels for storing liquid oxygen and nitrogen. Beginning in 1960 large field-erected storage tanks were produced to service the demands of the welding and steel industries for tonnage quantities of these industrial gases, *Fig. A.* Perhaps the largest vessels produced at that time were stripping and fractionating towers up to 3.35m (11 ft.) in diameter by 27.7m (91 ft.) high used in a helium production facility in the U.S., *Fig G.* Some of the units encountered operating temperatures as low as -170°C (-275°F).[13]

Very early in the development of LNG export/import schemes, 9Ni steel came into consideration for ship and land-based storage tanks.[30,31] Gaz de France started operating its test station at Nantes in 1960. In July that year a 500m^3 double walled, above-ground tank with an inner shell of double normalized and tempered 9Ni steel was commissioned to receive and store LNG, *Fig. D.* This tank was built without stress-relieving after welding. It has given perfectly satisfactory service for 28 years.

During 1961, Methane Transport, a French consortium, carried out an extensive program to convert a Liberty ship rechristened *The Beauvais* to test various LNG cargo tank designs, *Fig. P.* Two of the three experimental tanks were based on 9Ni steel; one was a 120m^3 aplexic multilobe design involving a great deal of welding, and the other was a 135m^3 double walled cylindrical design with the outer shell of 9Ni steel. Both designs performed satisfactorily.

During 1963-64 the first large liquefaction plant was being built in Arzew, Algeria, to serve the European markets. One of the two 11,000m^3 storage tanks was of 9Ni steel,[42] *Fig. C.* In the Gaz de France receiving plant at Le Havre, three 12,000m^3 9Ni steel tanks were built, *Fig. E.* All four of these earliest LNG tanks have now been in operation for more than 23 years with records of completely satisfactory service.

LNG schemes in the United States were developed primarily for peak shaving purposes, and involved 9Ni steel storage tanks from the beginning. In 1965, Alabama Gas commissioned a peak-shaving plant based on a 28,600m^3 9Ni steel tank, *Fig. B.* Two larger tanks (46,000m^3) were built in Hopkinton, Massachusetts, in 1967. These tanks have now accumulated 23 and 21 years of reliable service, respectively.

Although 9Ni steel has not been used as extensively in ship tanks as it has been for land-based storage, nevertheless it has an equally impressive record of reliability.

The first commercial-size tanker to incorporate 9Ni steel cargo tanks was the 25, 500m^3 *Jules Verne, Figs. I, J.* The cargo tanks were of an early cylindrical design developed by Gaz Transport.

Commissioned in 1965, the *Jules Verne* has been in continuous service since. By the end of 1987 it was the dowager of the LNG fleet, having completed 727 voyages, delivering almost 18,000,000m^3 of LNG and logging nearly 1,500,000 cargo kilometres (900,000 cargo miles). Again, the 9Ni steel cargo tanks have given completely satisfactory service.

Two more modern 85,200m^3 ships, the *Norman Lady* and the *Pollenger*, were built in 1973 with 9Ni self-supporting spherical cargo tanks of the Kvaerner-Moss design[34] *Fig. L.* The *Norman Lady, Fig K,* has operated over 788,000 loaded kilometres (490,000 loaded miles) on the Middle East to Japan route through 1987. In late 1986 the *Pollenger, Fig. M,* completed the then longest single trip of an LNG tanker, 17,700km (11,000 miles) from Indonesia to Everett, MA. The ship performed perfectly satisfactorily even though it had been laid up from 1983 to the fall of 1986. After that trip the ship was renamed the *Asaka Maru* and placed in service between Indonesia and Japan.

Record of 9% Nickel Storage Tanks

By 1988 a total of 189 field-erected 9Ni storage tanks had been built worldwide in export/import, peak-shaving or satellite installations, providing a total storage capacity of almost 125,000,000m^3 of LNG.[47]

These are aboveground double walled tanks with the inner shells constructed of 9Ni steel. Other types of tanks also in use are: (a) aluminum double wall designs, for a large part confined to smaller peak-shaving installations, (b) inground tanks with stainless steel membrane liners, concentrated in the Tokyo area of Japan, (c) prestressed concrete inground or aboveground units, and (d) several reservoirs constructed as frozen earthen caverns.

A majority of 9Ni steel storage tanks in service today are very large, as compared to the earliest tanks mentioned above. Peak-shaving units tend to be in the 50,000 – 60,000m^3 range, while export/import terminal tanks are generally from 60,000m^3 up to 135,000m^3 in capacity.

The initial design concept of a double wall structure with the inner shell of 9Ni steel and an outer shell of carbon steel continues to be used. In response to concerns about the consequences of postulated leaks or spills, however, considerable attention has been given to means of safely confining tank contents should they escape the primary vessel.[25,44]

Starting with simple moats, dikes and berms, designs have progressed to the current concepts of *double containment* structures where tanks are partially or completely enclosed within reinforced concrete shells, *Fig. N.* The three 80,000m^3 LNG tanks recently built for Abu Dhabi Gas Liquefaction Co. are examples of a double-containment design utilizing 9Ni inner shells,[28] *Fig. O.*

It is a tribute to the quality of materials and fabricating practices, and the standards of design and inspection established by the international regulatory codes, that there have been no instances of leaks or ruptures of 9Ni inner tank shells in the more than 28 years in which such tanks have been used.[26]

Operation Cryogenics – USA

Conducted by Chicago Bridge and Iron, U.S. Steel and The International Nickel Co. October, 1960.[11]

Impact and pressure tests were conducted on full-scale vessels of nine per cent nickel steel at -180°C to demonstrate the suitability of the steel for cryogenic structures when used in the quenched and tempered condition without stress-relieving after welding.

Description of Vessels

Operation Cryogenics included nine vessels altogether: one set of vessels fabricated from quenched and tempered plate, with and without stress-relieving after welding, and a second set from double normalized and tempered plates, with and without stress-relieving. This summary presents only the results from the as-welded vessels fabricated from quenched and tempered plates since this is the type of construction subsequently adopted for the inner shells of LNG tanks.

(a) Cylindrical vessels with hemispherical heads: 1.22m dia. x 3.75m x 9.62mm (4 ft. dia. by 13 ft. long, by 0.375 in. wall).
(b) Rectangular vessels internally stiffened: 2.44m x 2.44m x 9.62mm (8 ft. by 8 ft. by 0.375 in. wall).
(c) Design stress – 22.5ksi (15.65kg/mm^2).
(d) Welding electrode – E NiCrFe-2 high-nickel-chromium austenitic electrode (Inconel type).
(e) Plate properties – ASTM A 553 Quenched and Tempered Charpy V notch at -196°C (3/4 size specimens)
Longitudinal – 32-41 ft. lb., 38.7 average (52J*)
Transverse – 26-34 ft. lb., 31.8 average (43J*)
*Equivalent to 65J and 53.2J in full-size specimens.

Results of Tests

Cylindrical vessels were pressurized with liquid nitrogen at -196°C until failure.

Vessel	Burst pressure	Burst stress	Fracture initiation
No 1	2, 275psi (1.6kg/mm^2)	135, 500psi** (95.48kg/mm^2)	in longitudnal weld seam
No 2	2, 160 (1.52)	132, 500** (93.37)	in fill line fillet weld

**6.1 and 5.9 times the design stress

All fractures in plates propagated in a fully ductile manner by 100 per cent shear.

Rectangular vessels impacted at -196°C by multiple blows of a falling weight while under a nominal internal pressure of 70psi (.05kg/mm^2). Striking point was on the centre of one face. A 1,973kg (4,3401b.) weight dropping as a pendulum from a height of 5.8m (19 ft.) maximum.

The tank withstood seven impacts ranging from 53,121J to 112,585J (39,060 to 82,460 ft. lbs.) in kinetic energy before a steady loss of pressure indicated that a small crack had formed. The tank was permanently indented by 62mm (2.44 in.), and bulged by 33.8mm (1.33 in.). No gross failure occurred.

Vessel Tests in Italy 1964[14]

Burst tests were conducted on vessels of similar design to *Operation Cryogenics* in Italy in 1964 under the auspices of the ANCC. A burst stress of 107.75kg/mm^2 (152, 900 psi) was achieved in a vessel of quenched and tempered plates in the un-stress-relieved condition. This failure stress is 6.5 times the design stress. Strain gauge measurements during pressurization showed that the plates underwent considerable plastic yielding before rupture.

Burst Tests in Japan 1964

Burst tests were conducted in Japan in 1964 jointly by Nippon Steel Corporation and Ishikawajima Harima Heavy Industry Co.

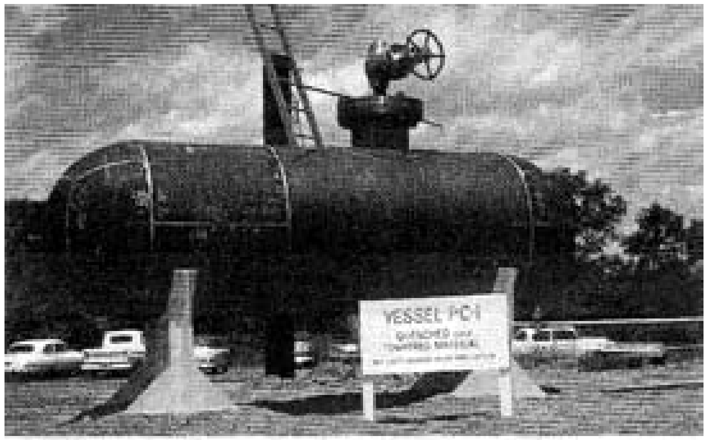
Description of Vessel

(a) Spherical vessel: 1.5m in dia., plate thickness 20mm.
(b) Design stress: 16.8kg /mm^2.
(c) Welding electrodes – Inco Weld A (Inconel type) and T 784.
(d) Pressurized to bursting by liquid nitrogen, -177°C to -187°C actual tank wall temperatures.

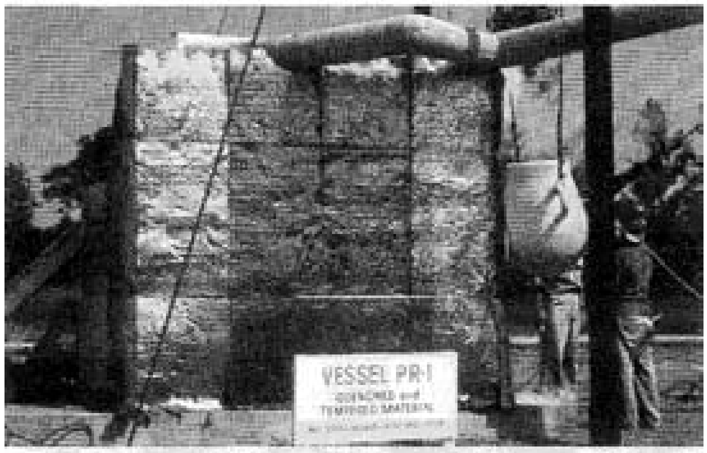
Results of Tests

(e) Rupture stress – 80kg/mm^2 (4.7 times the design stress).
(f) Tank deformation after rupture: radius increase 0.03 per cent.
(g) Fracture path: Initiated in vertical weld seams and propagated through weld metal over a total of 3.17m. Fractures entered base plate, showing 40 per cent ductile fracture and arrested in plate.

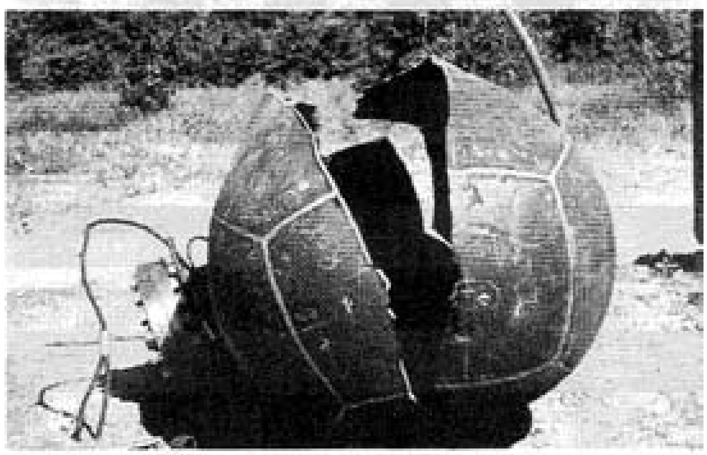
Figure H
Courtesy International Nickel Co.



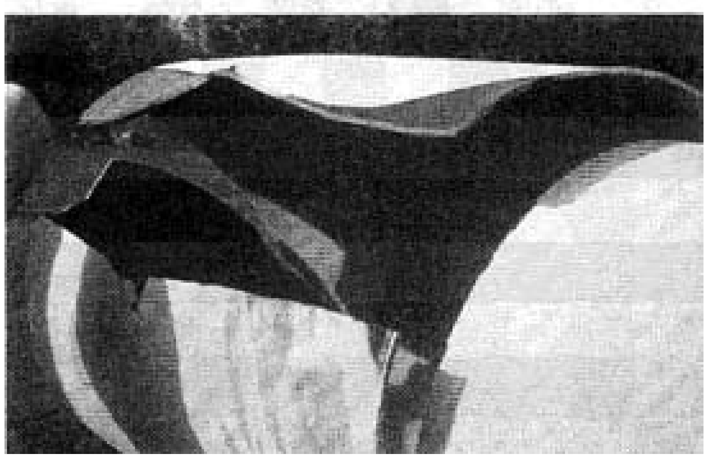
H1 – Test pressure vessel of quenched and tempered 9Ni steel not stress-relieved after welding



H2 – Simulated ship tank of 9Ni being impacted while filled with liquid nitrogen, quenched and tempered steel as-welded



H3 - Pressure vessel after failure at 6X design operating stress



H4 – View of failed pressure vessel showing ductile tearing type fracture and bending of plates

Part II
Resistance of Nine Per Cent Nickel Steel to Brittle Fracture

As noted in the preceding section, burst tests of prototype vessels demonstrated from a practical standpoint that 9Ni steel pressure vessels would withstand stresses of four to six times the nominal design stresses allowed by governing codes and, that when failure did occur, vessels fractured in a ductile manner.[11,14]

The consequences of a total brittle failure of a storage tank would be so serious, however, that more quantitative data on fracture properties were needed in order to analyze the structural behaviour of tank designs. The industry uses leak-before-failure criteria as one means of judging safe tank performance. That is, a vessel should be tough enough so that a crack would become evident as a leak before becoming large enough to initiate a spontaneous brittle fracture.

Designers needed to know how large a flaw a steel can tolerate before it is in danger from brittle fracture under foreseeable operating conditions. They also need assurance that the critical flaw size in a steel would be large enough to be reliably detected by the quality control inspection methods applied during fabrication. Furthermore, designers would like to predict how a tank might behave if a wall were ruptured initially by some major outside accident. In such an event a steel should be tough enough to stop a running crack before it could pose a major hazard to the structural stability of the tank.

Fracture mechanics tests offered the possibility of meeting such concerns, and consequently 9Ni steel has been extensively evaluated by the various test methods as they have evolved over the past 25 years.[15-27,29, 33-35]

Measurement of brittle fracture in nine per cent nickel steel

In order to apply the mathematics of classic fracture mechanics, a fracture must be initiated and propagate to complete failure under linear elastic plane strain, without energy being consumed by plastic flow.

When 9Ni steel has been tested by various fracture mechanics laboratory tests, however, it has been found to retain so much inherent ductility – even at the lowest cryogenic temperatures – that it is extremely difficult to achieve a completely brittle failure. When a crack starts, the steel's ductility allows the elastic energy around the crack tip to be partially dissipated by local plastic flow, causing the crack to blunt and arrest until the elastic strain rebuilds and initiates further step-wise propagation at increasingly higher stresses. This pop-in behaviour in laboratory tests has two practical implications.

First, it should be possible to conclude that if a crack should be initiated in a 9Ni tank, it should not immediately propagate catastrophically to complete failure but would progress by small increments to the point that it would exhibit the leak-before-failure behaviour being sought.

Secondly, the energy absorbed in the plastic flow phase of crack growth is not adequately accounted for in the classic fracture mechanics equations, and the laboratory tests, therefore, indicate lower crack-initiation and propagation stresses than the steel could actually withstand.

From a practical viewpoint, therefore, properties of 9Ni steels determined by the standard laboratory tests could be looked upon as quite conservative when analyzing the anticipated behaviour of actual tanks.

Gas Research Institute fracture toughness studies

As a consequence of the shortcomings of the standard laboratory tests to fully represent the toughness of 9Ni steel, an international study group was formed in 1981 by the Gas Research Institute (GRI), Chicago, IL. Six laboratory teams from the United States, Japan, and the United Kingdom were organized into a co-operative project focussed on the objectives of:

- ☐ Assessing the notch toughness levels typical of 9Ni steels produced commercially since 1970.
- ☐ Rationalizing and standardizing laboratory test methods for determining crack-initiation and crack-arrest properties, and improving the means of interpreting the results into predicting tank behaviour.
- ☐ Determining whether the effects of the mechanical crack-starter flaws used in laboratory tests can predict the role of natural fabricating flaws occuring in weldments.
- ☐ Resolving questions concerning the influence of welding conditions, weld metal, and heat-affected zones upon the fracture behavior of 9Ni steel weldments.[17]

Fracture toughness of commercial steels

The GRI consortium was able to survey 643 commercial heats of 9Ni steel made between 1970 and 1983, the period during which a majority of LNG storage and ship tanks were built.[29]

The only type of toughness data available for all of these heats was from the Charpy V notched-bar impact test, a quality acceptance test required in all specifications. The GRI survey clearly showed (1) that all heats considerably exceeded the minimum Charpy value of 34J (25 ft. lbs.) at -196°C required for quenched and tempered plates manufactured to ASTM A 553 Type 1, and similar specifications, and (2) that Chapry values which averaged in the 50-70J range in the early 1970s started to increase sharply in 1978 to reach an average well over 175J by 1983. The study determined that this improvement in Charpy values was directly related to improved steelmaking practices in which sulphur was reduced and other elements more closely controlled.

This survey gives a good deal of practical reassurance to tank builders and owners. As noted, at the time the majority of the tanks were built in the 1970s the toughness of 9Ni steel plates was running considerably above the minimum required in the specifications (50-75J average versus 34J minimum). The steels selected by GRI in its research program to determine crack-initiation and arrest behaviour had Charpy values from 35J to 230J Charpy at LNG temperatures, a range representative of tanks in service.

Even though it is generally agreed that Charpy test results cannot be quantitatively translated into fracture-initiation or fracture-arrest values, the results of the GRI research showed at least qualitative parallels between Charpy and resistance to brittle fracture properties. That is, no steel with high Charpys had low resistance to crack initiation or propagation, and vice versa.

Given the Charpy levels found in the survey, and accepting a general parallel between transverse Charpy and fracture toughness, the GRI research reinforces the long history of failure-free service established by 9Ni steel storage tanks.

Measuring fracture toughness by small scale tests[36,40,41]

A large amount of the effort in the GRI project was devoted to trying to adapt the various laboratory-scale fracture tests developed for less tough materials to accommodate the higher toughness properties of 9Ni steel. A full elaboration of the complexities of this part of the project is beyond the scope of this discussion.

Enough progress was made, however, to demonstrate that small-scale compact crack-arrest tests (CCA) could be correlated to the more costly large-scale tests conducted on wide plates, which are considered to closely simulate the situation of a vertical crack running in an LNG tank. The consortium concluded that the lower bound of crack arrest-values from such small-scale tests could provide conservative assessments of the suitability of production heats of 9Ni steel for LNG storage tanks.[41]

Once the rationalization of the tests was achieved, the project yielded significant data on the fracture toughness behaviour of five heats of commercial steels whose compositions, properties and plate sizes embraced the ranges that have been typical of LNG tank construction.

Fracture initiation

Question:
How large a flaw can be tolerated in a 9Ni steel shell before a spontaneous brittle fracture will be intiated under foreseeable operating stresses?

Examples:

(A) A large flat-bottomed LNG tank stressed to its API 620 Appendix Q design limit, 31.7 ksi; constructed of plate ranging from 14mm-28mm in thickness; plates having Charpy properties in the 50J to 100J range, representative of average minimum levels produced in the 1970s.

(B) A spherical ship tank subject to buckling and fatigue from wave action; plate thickness of 33mm; nominal membrane stress 23.8 ksi.

Findings: [34,36,40,41,45]

(A) A conservative intrepretation of crack tip opening displacement (CTOD) and wide plate tests reported by GRI, combined with the results of many earlier studies, indicates that at -196°C such steels should have a lower bound static initiation fracture toughness value (Kc) of 150 ksi root inches minimum, and be able to tolerate a through-wall crack of 360mm in length when designed to API 620.

If tanks were built to the ASME design stress of 23.75 ksi, as is more usual in the U.S. and Japan, the tests indicate that cracks on the order of 640mm could be tolerated without initiation of brittle fracture .[41,45]

(B) In the case of the ship tank a different set of tests indicated that fatigue cracks might grow to lengths between 300m and 1200mm, depending upon the stresses in a particular section of the tank, before they would become critical with regard to brittle fracture.[34]

Conclusions:

9Ni steel plates typical of the quality produced from 1970 to 1978 should have resistance to the initiation of brittle fracture far beyond that required to meet the leak-before-failure objective. The GRI study indicates that tanks built with steels produced with the improved steelmaking practices introduced in 1978 should have even higher resistance to brittle fracture.

The tests show that cracks in such more modern steels would have to be several metres long before they might initiate brittle fracture. Thus concerns are set at rest over the possibility that spontaneous tank failure might originate from plate or fabricating flaws. In the first place the nondestructive inspection techniques such as ultrasonic, magnetic particle, and dye penetrant, which are required by codes during tank construction, are highly sensitive. They are capable of reliably detecting flaws much smaller than the relatively great lengths of the through-wall cracks found to be critical in the GRI studies. Further reassurance can be taken from the fact that improvements in steelmaking and heat treating practices have reduced the incidence of plate flaws such as seams, splits and heat treating cracks. Likewise, the possibility of weld flaws such as hot cracking and lack of fusion has been largely overcome by improved control of the welding processes and careful nondestructive testing (NDT) inspection during fabrication and erection.[45]

Crack-Arrest

Question:
Is 9Ni steel tough enough to resist the brittle propagation of a running crack that might be caused by over-stress from a major external event, i.e., what are its crack-arrest properties?

Example:
LNG tanks built to either the ASME design stress of 160MPa (23.75ksi) or the British Standards Institute value of 260MPa (37.7ksi). Plate qualities representitive of the 50-110J Charpy range of the 1970s or the 200-250J range of more recent production. Plate thicknesses from 14mm to 28mm.

Findings:[41]

Small scale compact crack-arrest (CCA) tests can be correlated to larger scale wide plate tests, and used to develop a conservative approach to assessing the ability of a plate to arrest a running crack. The GRI project results indicated that the thicker plates with toughnesses in the 50 to 110J Charpy range had lower-bound crack-arrest values (Ka) from 110 to 160MPa root metres, and that the steels with Charpy values in the 150 to 220J range had Ka values from 250 to over 350MPa root metres at LNG temperatures.

The ranges of sizes of running cracks that would be arrested in 28mm plate at the two design stress levels therefore are indicated to be as follows:[43]

Design stress	160MPa (23.75ksi)	260MPa (37.7ksi)
Charpy 50-110J	285mm minimum	117mm minimum
Charpy 150-200J	1, 700 and over	590 and over

The test results for plates thinner than 28mm characteristic of the mid and upper courses of an LNG tank were found to be even more highly conservative. In the thinner test pieces a smaller portion of the cross section is subjected to pure plane strain, and a greater portion of the total fracture energy in dissipated in plastic flow of the ligaments near the surface.

Again the fracture toughness calculations do not fully accommodate this large amount of plastic flow that occurs in thin sections of 9Ni steel with its high ductility. Therefore it is believed that plates under 28mm in thickness would have crack-arrest values at least 25 per cent higher than those shown by the thicker test pieces.[41]

Conclusions:

The designers and owners of LNG tanks should be reassured that 9Ni steel is capable of arresting large running cracks before they reach a length at which they pose a threat of propagating brittle fracture. One analyst has stated that if a rupture in a tank wall exceeds 200mm in length, no matter how it is generated, the tank would become unservicable because of bulging and leaking.[46]

Thus, if a steel is tough enough to arrest cracks up to at least 200mm long it has met the leak-before-failure objective. The GRI programs are reassuring on another concern. They show that it is extremely unlikely that 9Ni tanks will fail from the catastrophic over-turning or unzippering types of brittle fracture that some have postulated in the past.

Fracture toughness of welds

There have been many questions in the past about the effects of welds on the fracture resistance of 9Ni tanks.

They have arisen from the facts that 9Ni steel tanks are not stress-relieved to mitigate possible effects of the heat of welding, and that 9Ni steel is welded with non-matching filler metals. Consequently the GRI programs included studies to determine whether brittle fractures would initiate and propagate preferentially in heat-affected-zones of welds; how the lower strength and modulus, and higher toughness of the high-nickel, austenitic weld metal affect fracture behaviour of the weldment; and how well the effects of naturally occurring weld flaws correlate with the artificial flaws used in laboratory test pieces.

Effects of heat-affected zone

Question:

Does the heat-affected-zone (HAZ) in a 9Ni steel structure have lower toughness and offer a path for the preferential initiation and propagation of brittle fracture?

Example:

Weldments tested on a laboratory scale in the GRI and other investigations. Welds made in 9Ni plates of several toughness levels using low and high heat-input cycles and three nickel base filler metals. Crack-initiation (CTOD) and crack arrest (CCA and wide plate) tests were made with the starting flaws located in the various zones of the weld.

Findings: [37]

The HAZs of 9Ni steel welded with nickel-base consumables were found to have no greater susceptibility to initiating brittle fracture than their parent base plates. When cracks were intentionally started in the HAZs they diverted into the lower strength, higher ductility fusion zone and weld metal within short distances, and thereafter fracture was by ductile tearing. Crack-initiation resistance (CTOD) values of the HAZs were equal to or higher than the base plate in steels with Charpy values above 50J. In the case of one heat with Charpy values of 50J and below, CTOD values of the HAZ were slightly lower than the base plate, but the crack path still arrested in the fusion zone.

Crack-arrest properties in the HAZ were also equal to or superior to the base plate. At LNG temperatures all weldments had crack-arrest (Ka) values of at least 150MPa root metres, equivalent to stopping a running crack within 560mm. The higher toughness base plates had higher crack-arrest values in the HAZ. In the lowest toughness steel tested (50J), when stressed at 25 per cent above the Ka of the base plate, the fusion zone of the weld showed a Ka of 163MPa root metres, and the crack arrested within 25mm while still in the HAZ. Varying the welding conditions from low to moderately high heat in-put procedures had negligable effects on crack-initiation or crack-arrest values.

Conclusions:

The excellent toughness properties of 9Ni steel plates are retained in the as-welded condition when welded with austenitic nickel base welding products. Since crack-arrest values of the welds are at least equal to and generally superior to crack-initiation toughness of the base plate, and fractures starting in the HAZ quickly divert to the lower strength fusion zone and weld metal, the fracture behaviour of a tank would be ruled by the fracture toughness of the base plate and the tear strength of the high nickel weld metal. Designers and owners can be reassured, therefore, that with proper selection of steel quality and welding procedures LNG tanks will meet the desired leak-before-failure objective in the as-welded condition.

Moreover, it would appear that even if a low toughness plate were to suffer the initiation of a brittle fracture, the crack would be halted as soon as its path encountered a weld. Following this reasoning, one can speculate that the width of a shell plate may well set a practical limit on the maximum length to which a vertical crack would propagate. The potential for further rupture would then depend upon the ductile tear strength of the weld. These findings provide additional evidence against the possibility that 9Ni steel tanks might suffer an unzippering type of catastrophic failure.

Effect of mismatch of properties between weld and plate

The nickel-base austenitic alloys used for welding 9Ni steel produce weld deposits lower in strength and higher in ductility than the parent base plates. There is also a mismatch in modulus of elasticity between the weld metal and base plate. For example Inco Weld A and similar products – 70 Ni-15 Cr-2 Mn-1.5 Mo, and AWS E NiCrFe-2 and E NiCrFe-3 – used widely for fabricating LNG tanks, produce tensile strengths in the 63,000kg /mm^2 (90,000psi) range, and yield strengths of 37,000kg/mm^2 (53,000psi) range. Base plates of 9Ni steel to ASTM 553 Grade A and other similar specifications require minimum tensile and yield strengths of 100,000psi T.S. and 75-85,000psi Y.S., respectively. Therefore, there have been discussions in the past as to whether these mismatches might not act to concentrate stresses in the vicinity of welds, and thereby reduce the anticipated structural stability of a tank.

Question:

What effect does the mismatch of properties between 9Ni steel base plates and nickel-base weld deposit have on the structural behaviour of LNG tanks?

Example:

The weldments tested in the investigation of heat-affected zone properties were utilized to determine the relative roles of the heat-affected base metal and the weld deposit in fracture initiation and arrest.

Findings:[37]

As noted previously the crack-initiation resistance of the HAZ in modern steels was no less than that of the parent base plate. There was no indication that the mismatch in properties between weld and base plate made the overall weldment any more sensitive to crack initiation. The weld properties did come into play, however, once a crack was initiated in the base plate or the HAZ, for the fracture path diverted into the lower strength weld metal where the tear resistance of the high nickel material became the governing factor.

This behaviour is ascribed to the effect of both the lower yield strength and lower modulus of elasticity of the austenitic weld metal on the concentration of strain existing around a crack tip. The crack tends to be driven towards the lower strength area of the weld metal, rather than continuing its path in the stronger HAZ as directed by the external load.

Conclusions:

It is apparent that the mismatch in properties between weld and base plate does not increase the danger that an LNG tank will fail from brittle fracture. In fact the reverse seems to be true, and the mismatch may produce a practical benefit. It is the reason that welds act to halt, and therefore limit the propagation of brittle fractures.

Influence of natural weld defects on fracture behaviour

Brittle fractures are initiated at some discontinuity in a structure which acts as a point of stress concentration.

It is therefore important to know not only how large a flaw can be tolerated in an LNG tank, but also whether different types and configurations of flaws may have different effects on initiation of fracture.

A worldwide literature review by GRI determined that out of 21,533 pressure vessels surveyed between 1962 and 1972, there were records of 140 failures. Only three cryogenic tank failures were listed: one LNG tank of aluminum, and two ethylene tanks also of aluminum.[32]

No failure of an LNG tank involving 9Ni steel has been recorded to date.

The GRI study indicted that at least 50 per cent of the failures were associated with defective welds, the most common defects being lack of fusion, lack of penetration and hot cracking.

Tank designers and users, therefore, need to know how well laboratory tests using sharp artificial mechanical notches are able to predict resistance to fracture as it might be influenced by natural weld defects in 9Ni steel. Additionally it would be useful to find out the kinds of welding procedures that can lead to particular types of defects in 9Ni steel. Finally, assurance should be developed that quality control inspection procedures are fully adequate to detect critical weld defects.

Questions:

(A) Do fracture initiation and arrest values determined with mechanically notched laboratory test specimens accurately reflect the fracture resistance of 9Ni steel weldments containing natural weld flaws?

(B) What welding practices lead to various kinds of flaw in 9Ni steel weldments?

(C) Are inspection procedures adequate to detect the types of weld flaws that are critical to the fracture toughness of 9Ni steel storage tanks?

Example:

Fracture initiation and arrest tests pieces welded by procedures selected to promote lack-of-fusion and cracking in weld metal and heat-affected-zones.

Findings:[38]

9Ni steel was quite insensitive to welding conditions expected to produce weld defects. It was not possible to produce hot cracking in the fusion line or other areas of the HAZ, even when intentionally introducing excess hydrogen in the shielding gas. Cracking could be produced in the austenitic weld metal by welding under severe restraints, but no under-bead cracking could be produced in the HAZ. It was possible to produce lack of fusion in the controlled way by contaminating one side of the weld kerf with a solution of magnesium oxide before welding. Weldment properties did not seem to be noticeably affected by changing heat inputs or travel speeds during welding.

A natural lack-of-fusion flaw occuring at the weld metal/fusion zone interface had the same effect on fracture initiation and arrest as did a mechanical notch placed in the same location. That is, when a fracture was initiated at the tip of a lack-of-fusion flaw it diverted after a short distance into the softer, weaker austenitic weld metal, and thereafter fracture was controlled by the tearing resistance of the weld metal. The CTOD values for fracture-initiation resistance of the lack-of-fusion flaws were quite similar to the values with the mechanical flaw. In crack-arrest tests when a running crack was aligned with the lack-of-fusion flaws, Ka values were also comparable to those of the base plate. All weldments made with nickel-base rods had Ka values above 150MPa root metres, which would assure leak-before-failure behaviour, and reliable detectability well within the sensitivity of quality control inspection methods.

Conclusions:

The LNG industry can be reassured by the results of the GRI studies showing that conventional quality control inspection methods properly applied should detect welding flaws far smaller than the sizes at which they would be critical for brittle fracture initiation.

The GRI results have a number of other practical implications. In the first place, the attempts in the laboratory to produce flaws in a controlled way revealed that 9Ni steel when welded with nickel base austenitic alloys was insensitive to under-bead cracking and the effects of hydrogen. Apparently the higher ability of the austenitic weld metal to absorb hydrogen reduces the amount available to enter and embrittle the base metal in the fusion zone. It was also found that 9Ni steel has low sensivity to thermal cracking in the heat-affected-zone probably due to the fact that its rehardened structures are much tougher than those formed in lower alloyed pressure vessel steels of higher carbon content which do show susceptability to thermal cracking. Lack-of-fusion flaws remain, therefore, as the most likely weld defect that could act to initiate brittle fracture.

The GRI studies gave assurance that laboratory tests would adequately predict the failure-initiating effects of a lack-of-fusion flaws, and that the resistance to brittle fracture of weldments containing lack-of-fusion flaws was comparable to that of the parent base plate. Consequently welds as well as base plate meet the leak-before-failure objective.

The crack-arrest studies were particularly reassuring in that they consistently showed the nickel-base weld metal acting to stop the propagation of cracks, diverting the path of a running crack into the lower strength high ductility weld metal which is not subject to brittle fracture. It is apparent that flaws in vertical welds would be the most damaging, and that if the length of flaws or consequent cracks are held to less than 500mm, a tank would not be subject to brittle failure.

Available inspection techniques should be fully adequate to detect flaws of such magnitude.

Influence of residual stress in as-welded tanks

ASME Code Case 1308-4 in 1963, approving the use of 9Ni steel in the as-welded condition, was a key step in the evolution of LNG storage tank design.

This ruling permitted the construction of large field-erected tanks that could not feasibly be thermally stress relieved after welding. Since, in general, residual stresses resulting from welding could be assumed to interact with operating stresses, the question arises as to whether they introduce variables in the calculations for initiation and propagation of brittle fracture in as-welded LNG tanks.

In theory, a residual stress field set up around the tip of a flaw in a weld-affected area should be accounted for in determining the plane strain conditions influencing fracture initation and propagation. In practice, however, the classic fracture mechanics tests do not lend themselves to quantitative measurement of a residual stress component.

Question:

What is the possible role of residual welding stresses in the fracture resistance of LNG tanks in the as-welded condition?

Example:

A conventional double wall LNG storage tank with a 9Ni steel inner shell designed and built to API 620 Appendix Q or BS 5387 in which thermal stress relief after welding is not required.

Findings:

The original acceptance of as-welded 9Ni tanks by regulatory codes was based in part on successful tests to destruction of prototype vessels which had been given no thermal stress relief.[5,11,14]

Although it is not feasible to thermally stress relieve field erected storage tanks, an alternative means of stress relieving does result from the mechanical stressing that occurs during the hydro testing of a completed tank. The codes require a water test at loads to 125 per cent of the future load by the product. It has been more recently suggested that the water test require filling to the full product level in order to compensate for the difference in density between water and LNG.[44]

Clearly gross loads of such levels will cause plastic yielding to occur in localized zones where peak residual tensile stresses might have been generated during welding. The effectiveness of such mechanical stress relief has been demonstrated in laboratory tests; by loading of specimens to only 60 per cent of the nominal yield strength of the base plate, peak stresses were reduced from 32kgf/mm^2 to 23kgf/mm.[45]

Conclusions:

There is a consensus in the industry that the required hydro-test has reduced concerns as to the possible damaging effects of residual stresses on the fracture resistance of as-welded tanks. In fact the process is viewed as a major contributor to the record of reliability achieved by 9Ni LNG tanks.[46]

January, 1989

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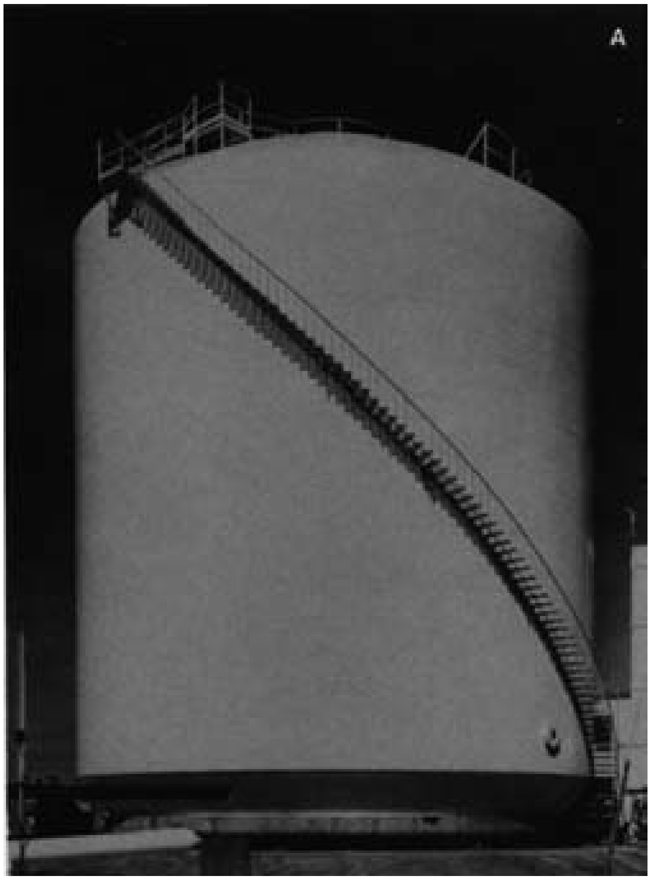


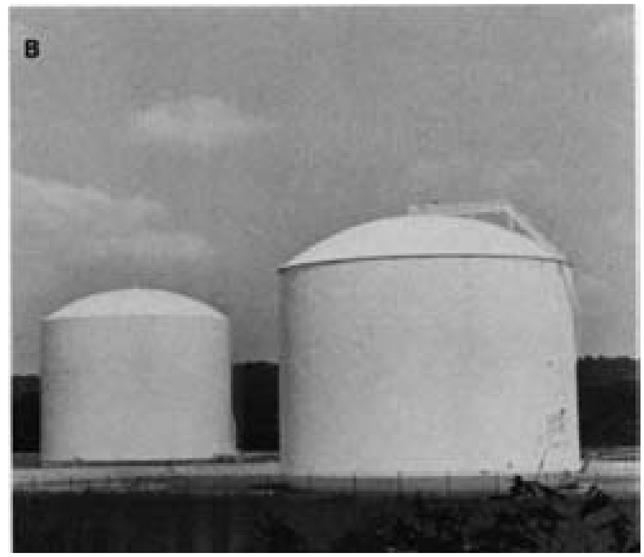


Figure A
Liquid nitrogen tank for Air Reduction Corp, Industry, CA – 1964. Courtesy Chicago Bridge and Iron

Figure B
Liquefied natural gas peak-shaving tank, Alabama Gas Co. – 1965. Courtesy CBI

Figure C
Liquefied natural gas storage tanks for SONATRACH, Arzew, Algeria – 1964. Courtesy Constructions Metallique de Provence

Figure D
LNG tank of 9Ni steel built for Gaz de France in Nantes, France – 1960. Courtesy GDF

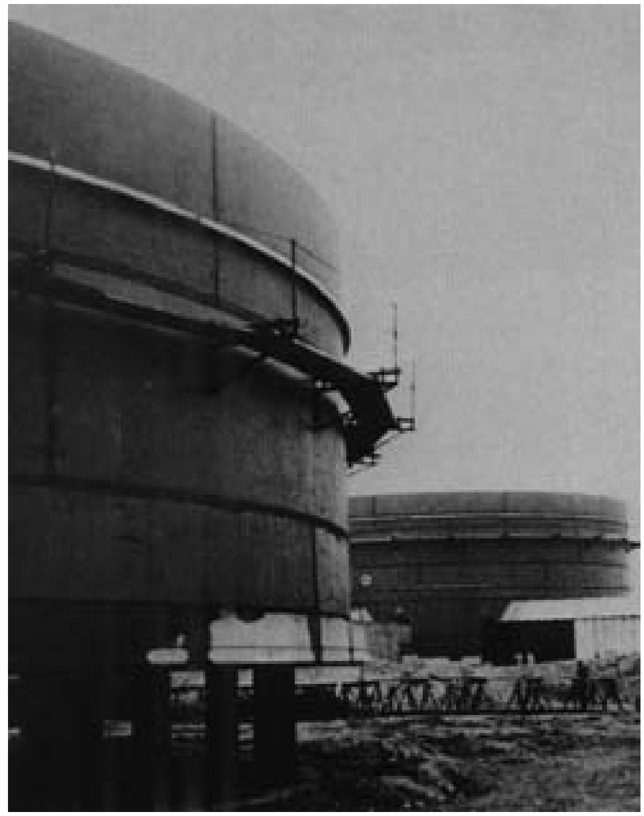


Figure E
Two of three 9Ni tanks at Le Havre built to receive LNG from Algeria. Courtesy GDF

Figure F
9Ni cryogenic storage tanks for liquid oxygen. Courtesy Graver Tank Co.

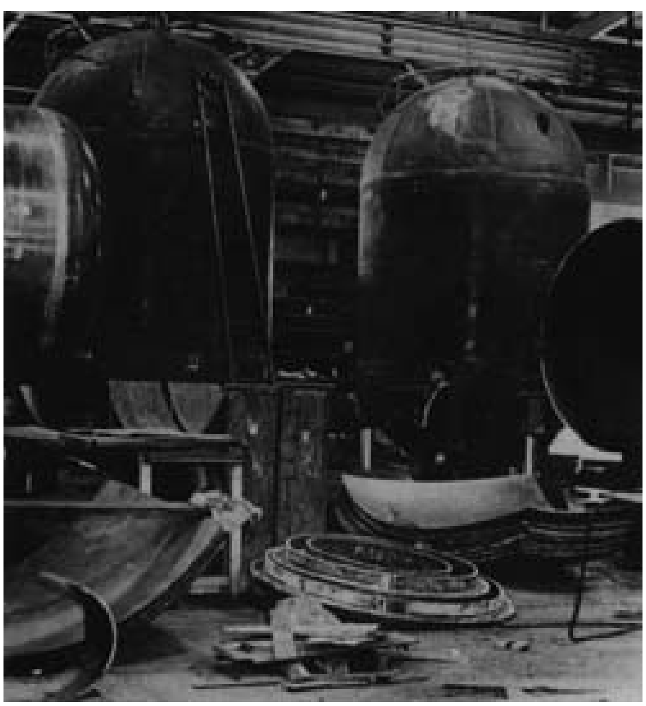


Figure G
9Ni towers built for National Helium Co., USA – 1963.

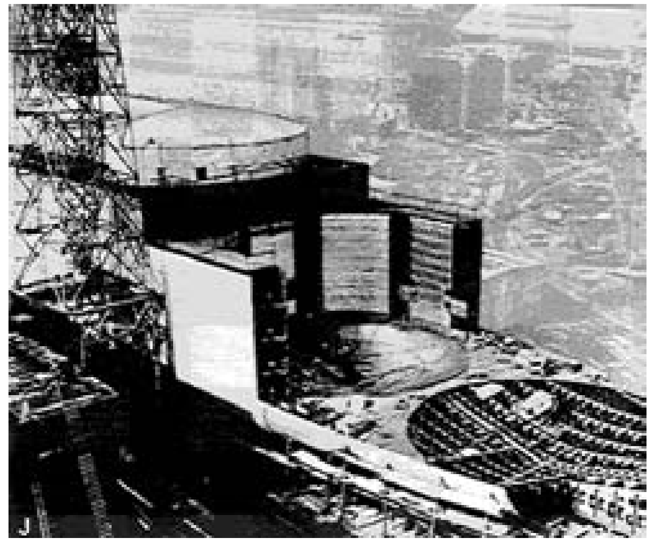
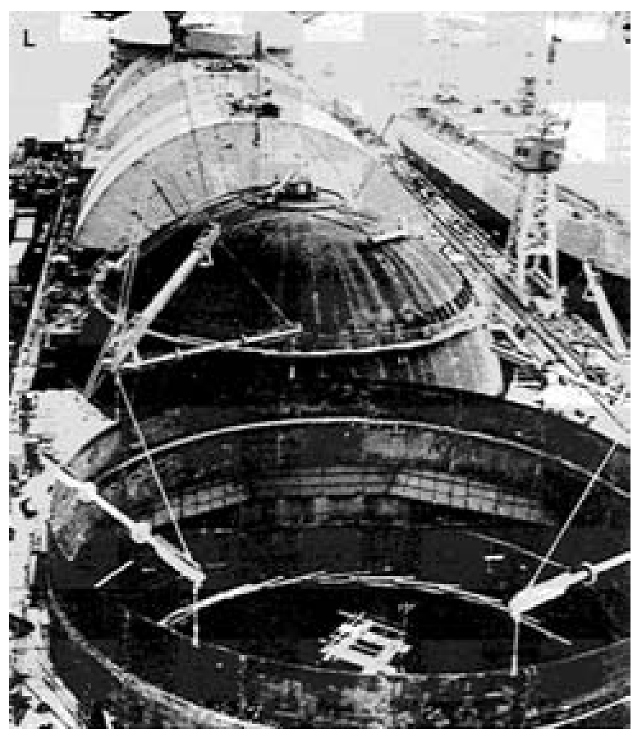


Figure I
Jules Verne, the first commercial LNG tanker with 9Ni cargo tanks, launched in France in 1964. Courtesy Ateliers et Chantiers de la Seine

Figure J
Construction details of 9Ni cylindrical cargo tanks in *Jules Verne.*

Figure K
Norman Lady, LNG tanker with spherical 9Ni tanks launched in Norway – 1973.
Courtesy Moss Rosenberg Verft

Figure L
Fabrication of 9Ni tanks in the *Norman Lady* using sub-arc, metal arc, and automatic pulsed metal inert gas welding methods.



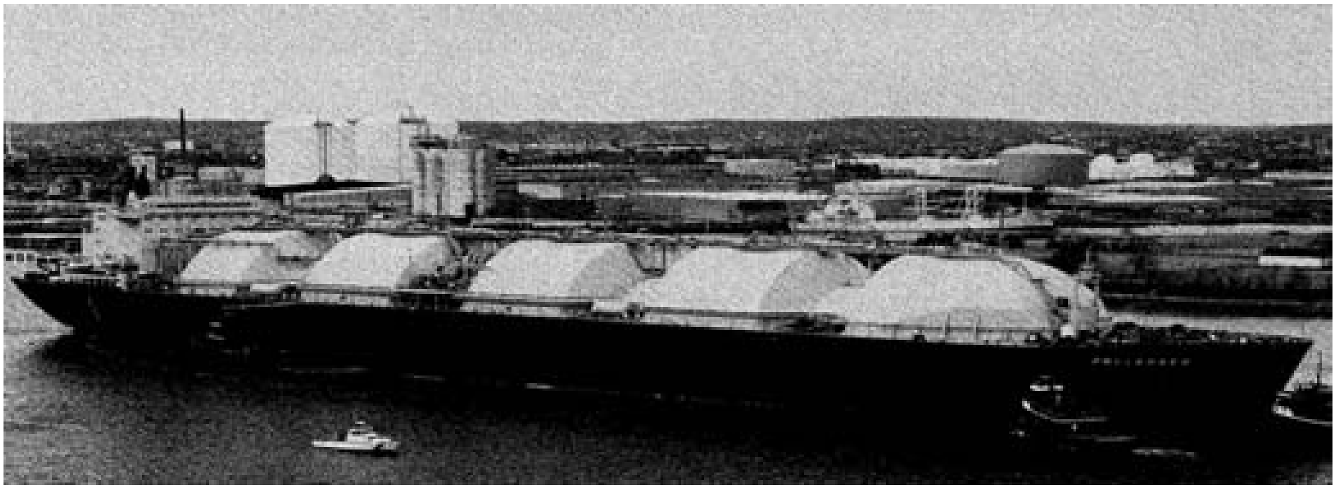
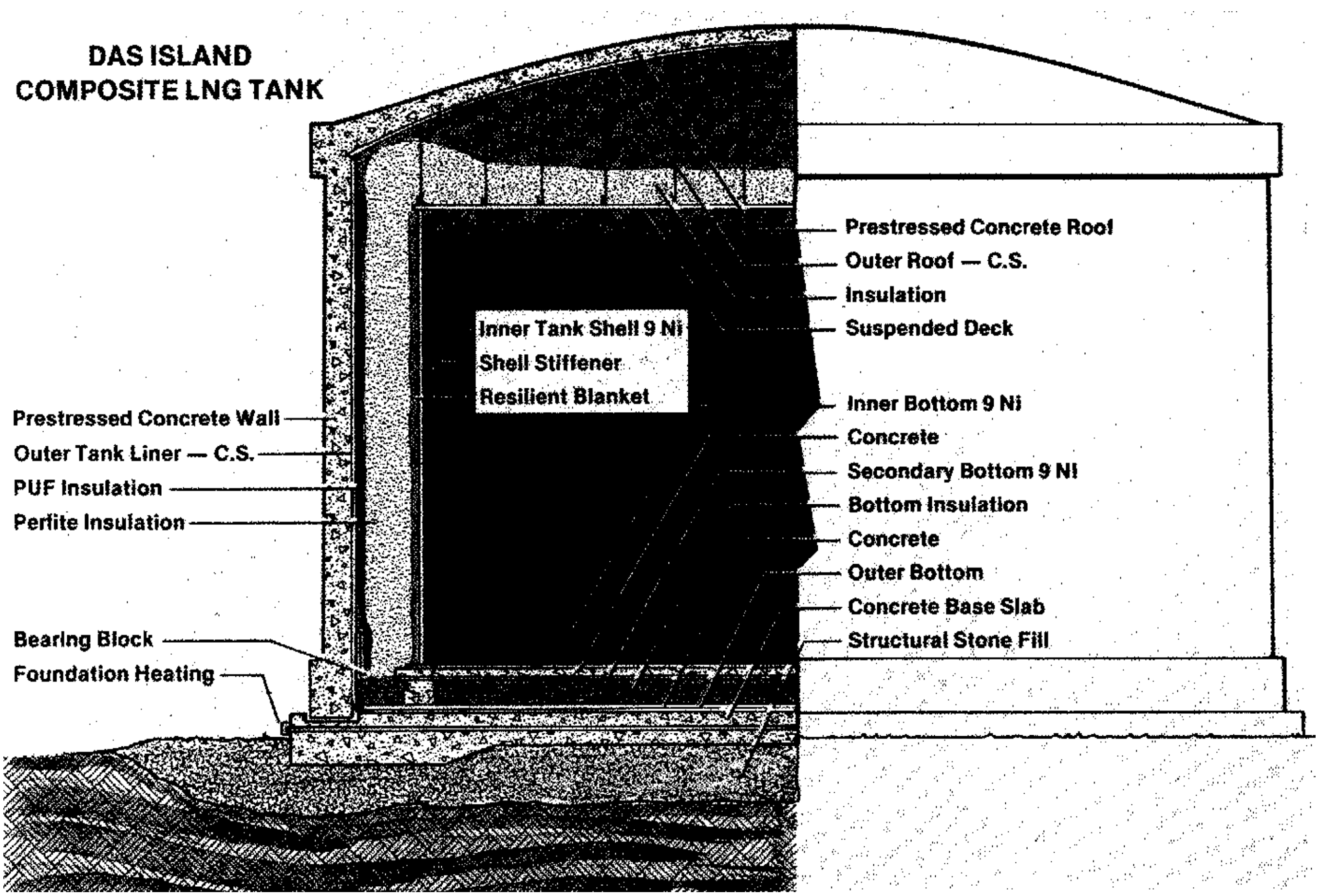


Figure M The *Pollenger,* sister ship to the *Norman Lady.*

Figure N A double containment LNG storage tank, a recent design featuring an inner shell of 9Ni steel, an outer shell of carbon steel, with the whole unit completely surrounded by a reinforced concrete shell. Courtesy Chicago Bridge and Iron.



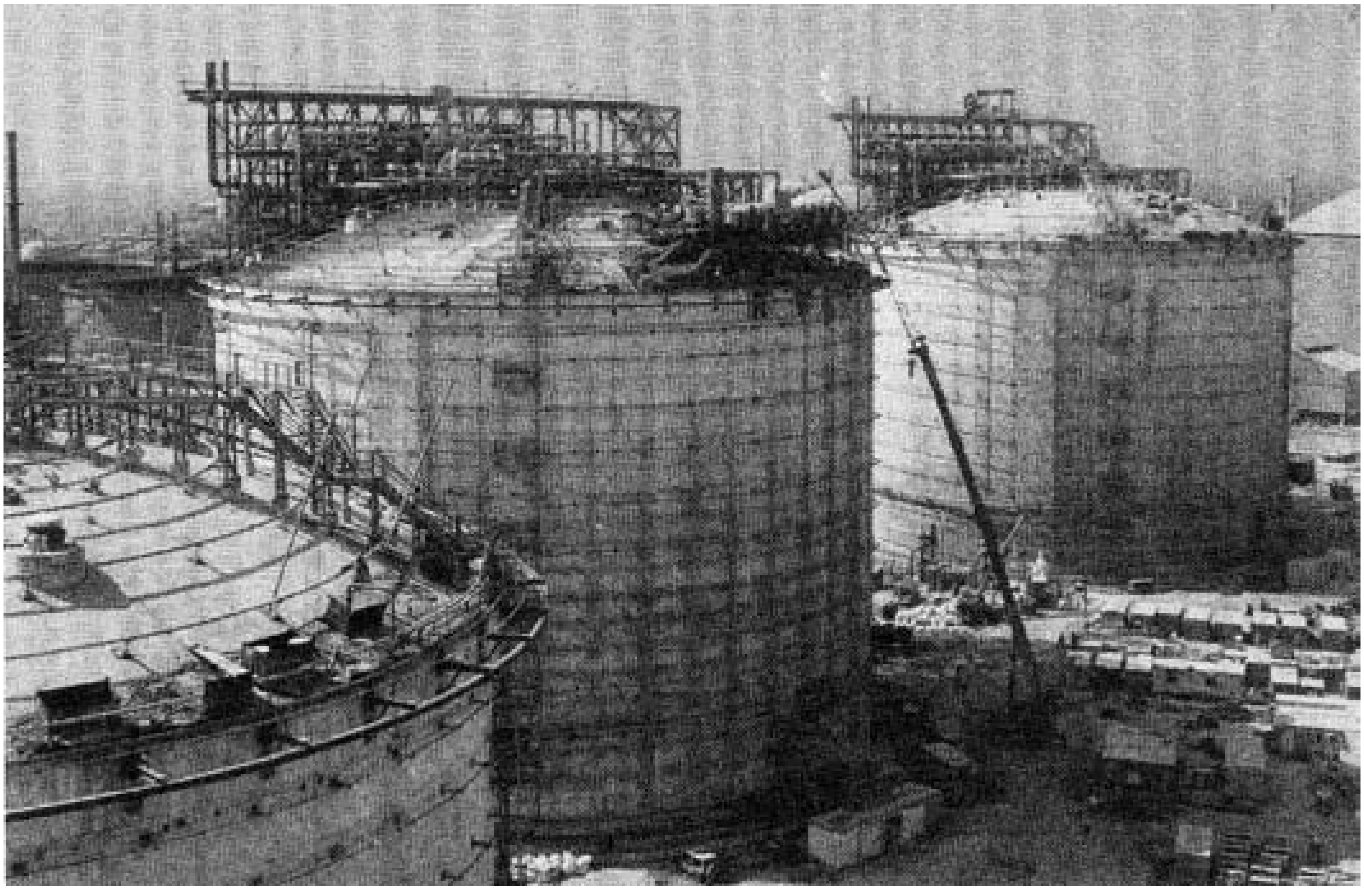


Figure O Double containment 80,000 cubic metre LNG tanks under construction, Das Island, Abu Dhabi Gas Liquefaction Co.

Figure P Experimental tanker *Beauvais,* rebuilt in 1960-61 by Gaz Transport to test several designs of cargo tanks.