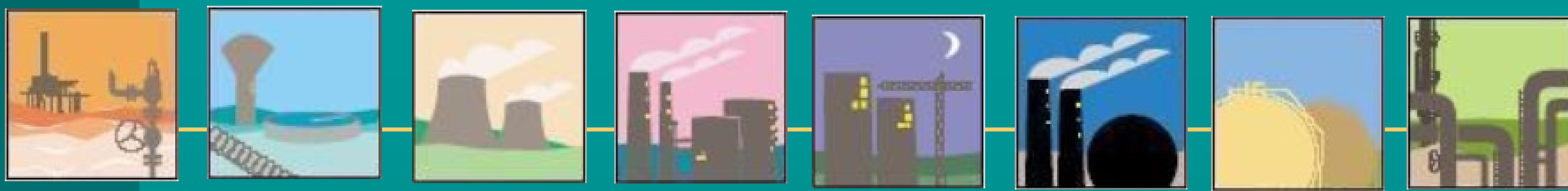
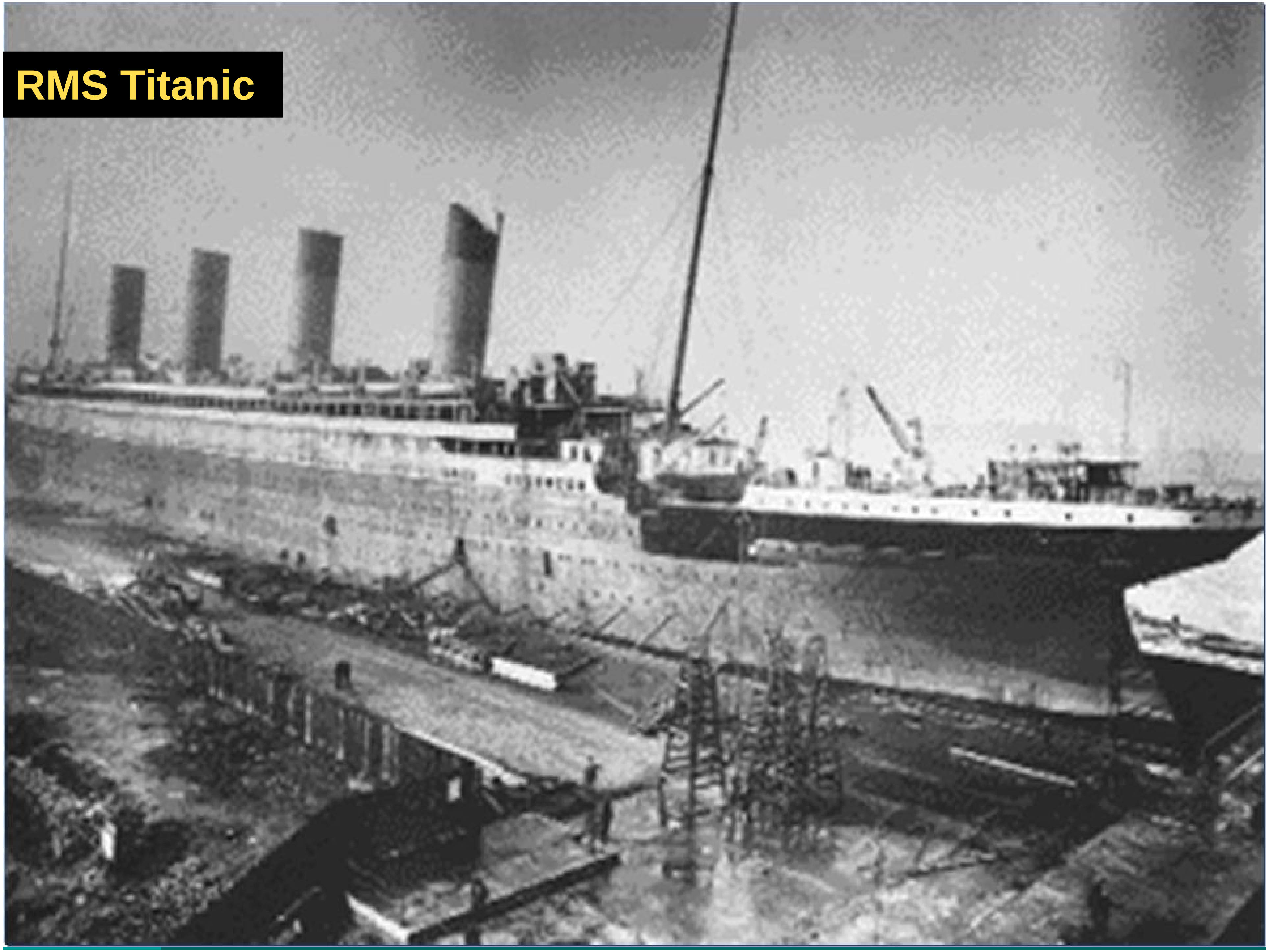


# Ductile-to-brittle transition temperature (DBTT) in steels and its significance in design and manufacturing

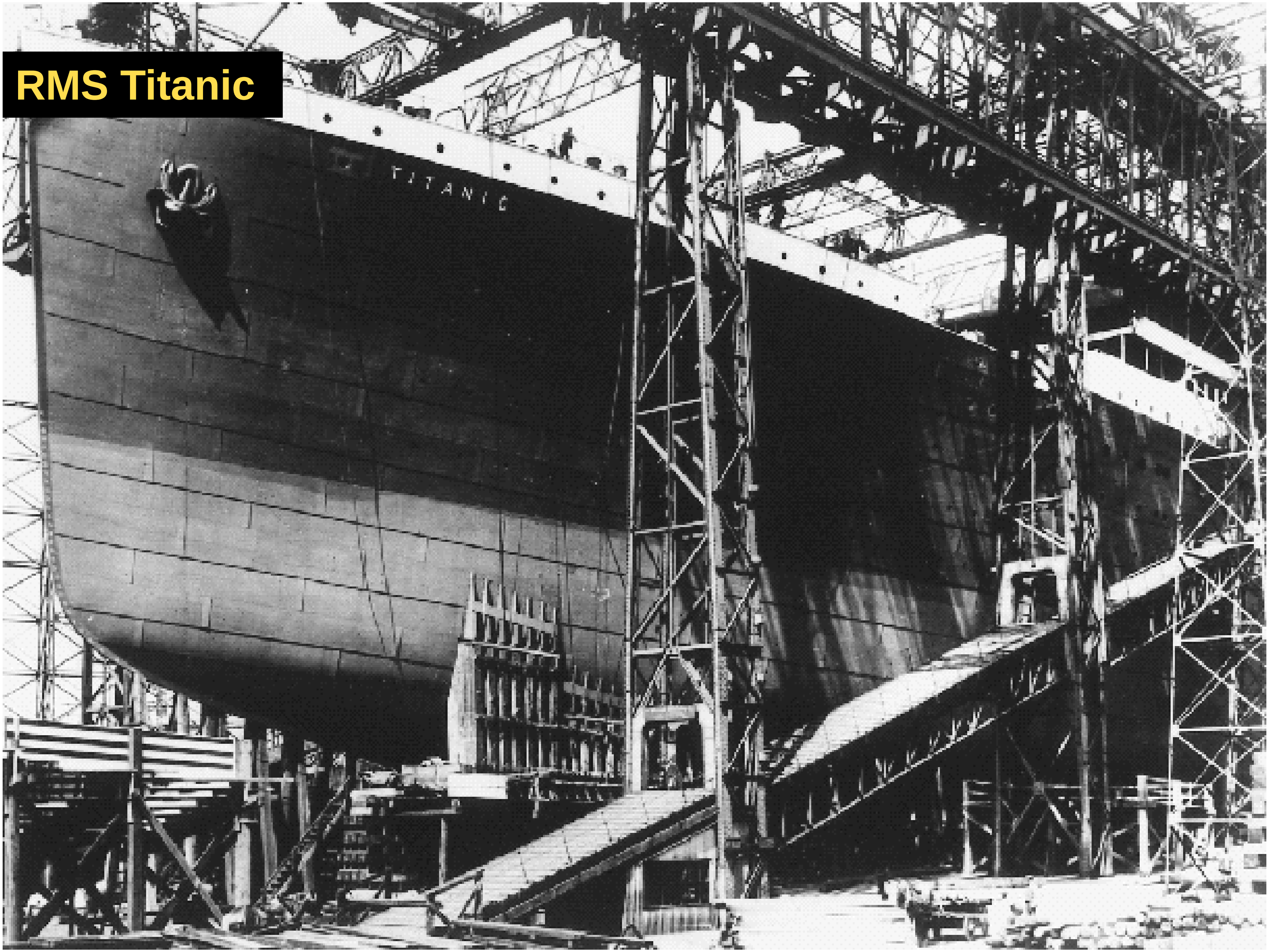
By: Kamran Khodaparasti

Tehran, June 2009

# RMS Titanic

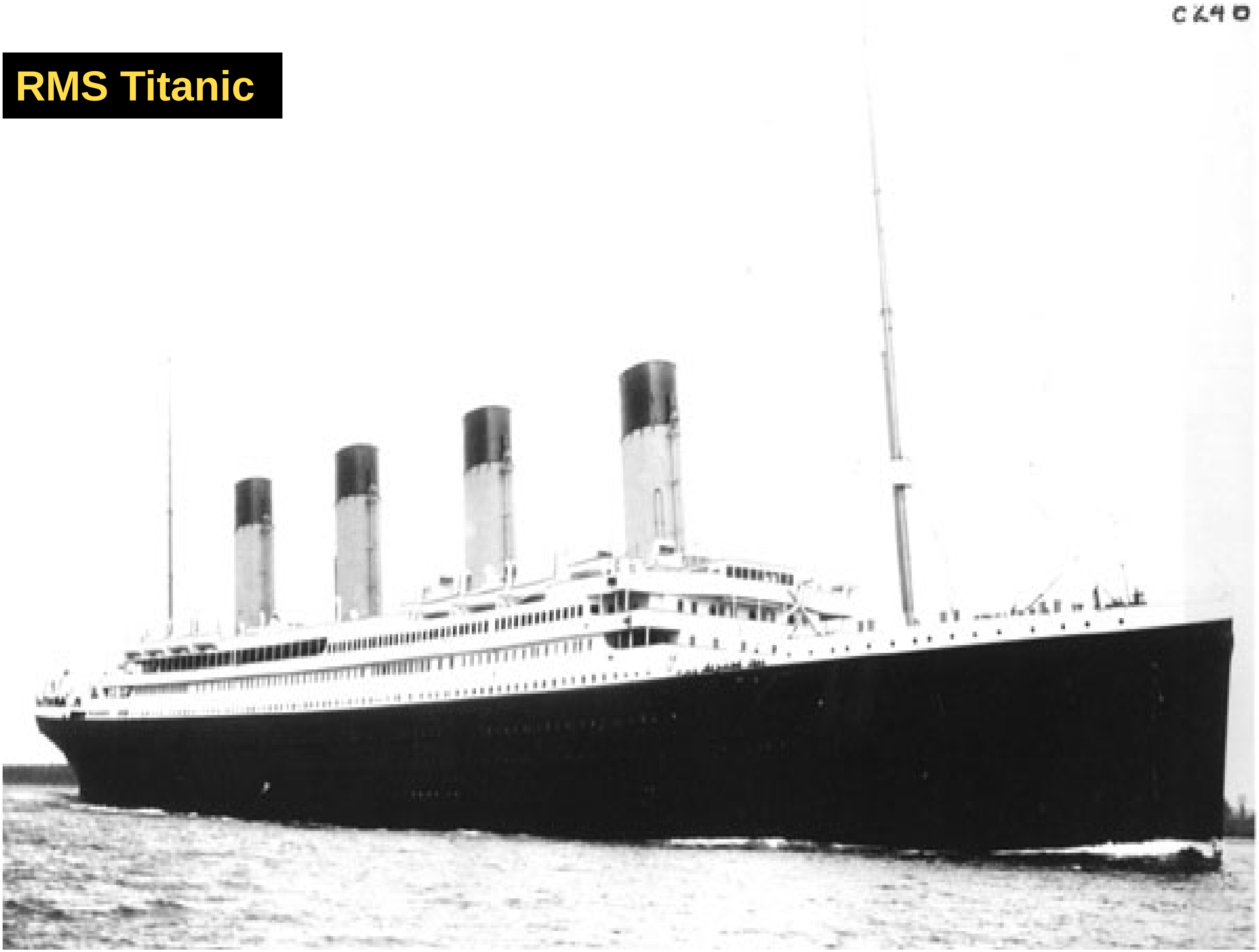


# RMS Titanic

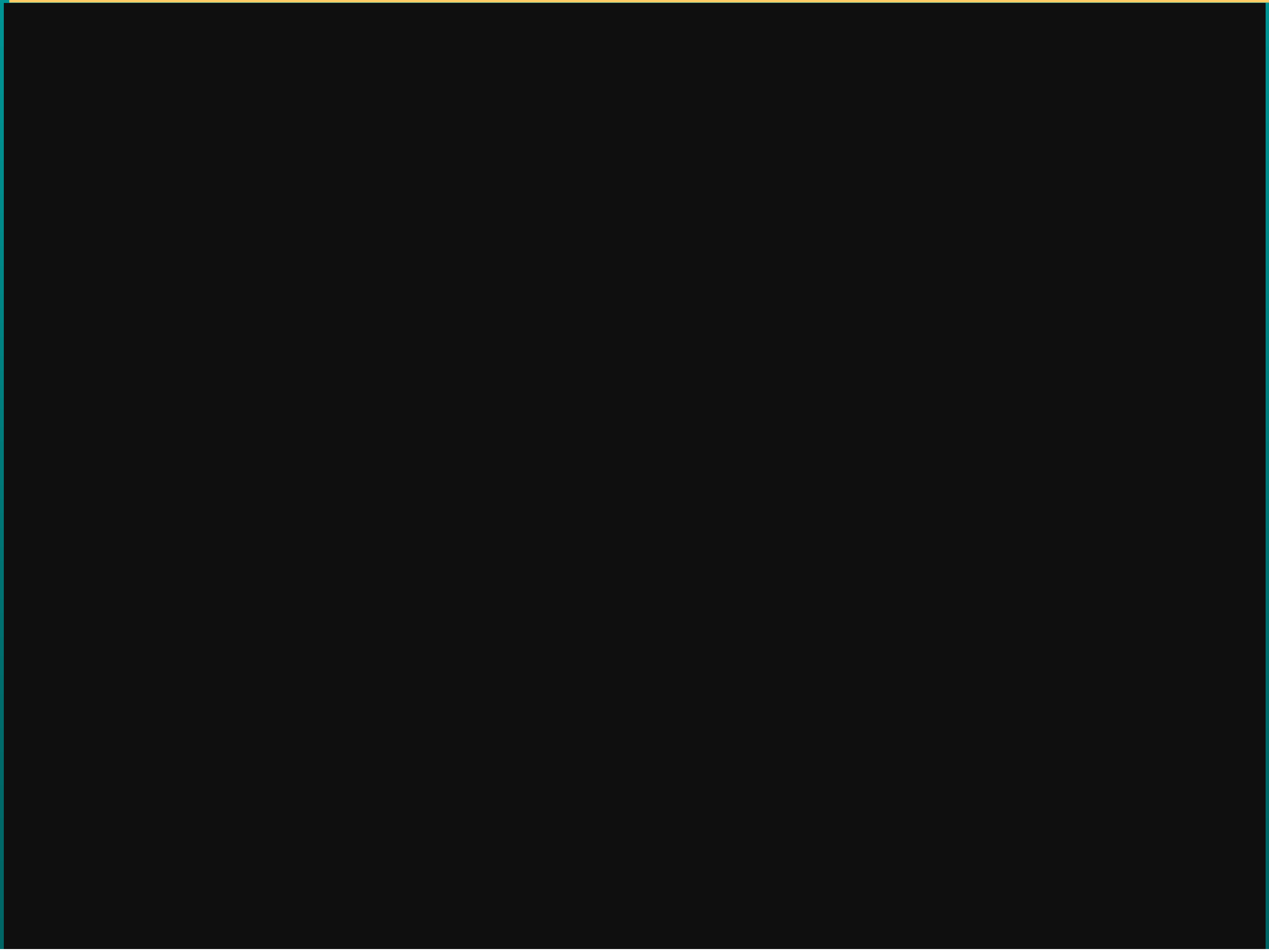


# RMS Titanic

# RMS Titanic



# Titanic features

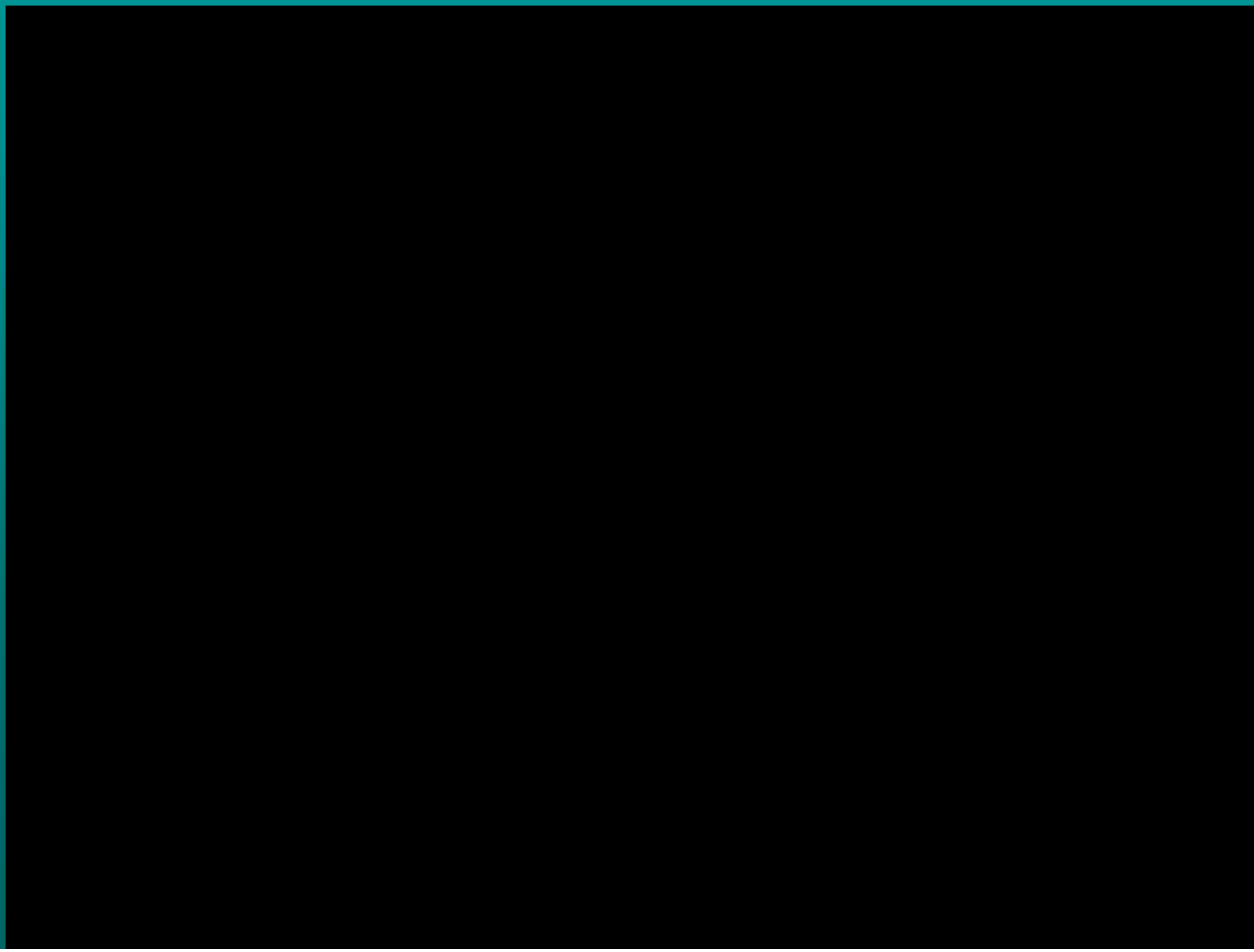



RMS Titanic, April 14, 1912


TITANIC
HULL
ICEBERG

# Titanic sinking

# Rediscovery of the Titanic (Possible factors in the sinking)



# World War II emergency ship building program (USA)

Ships production over the years 1941-1946 :

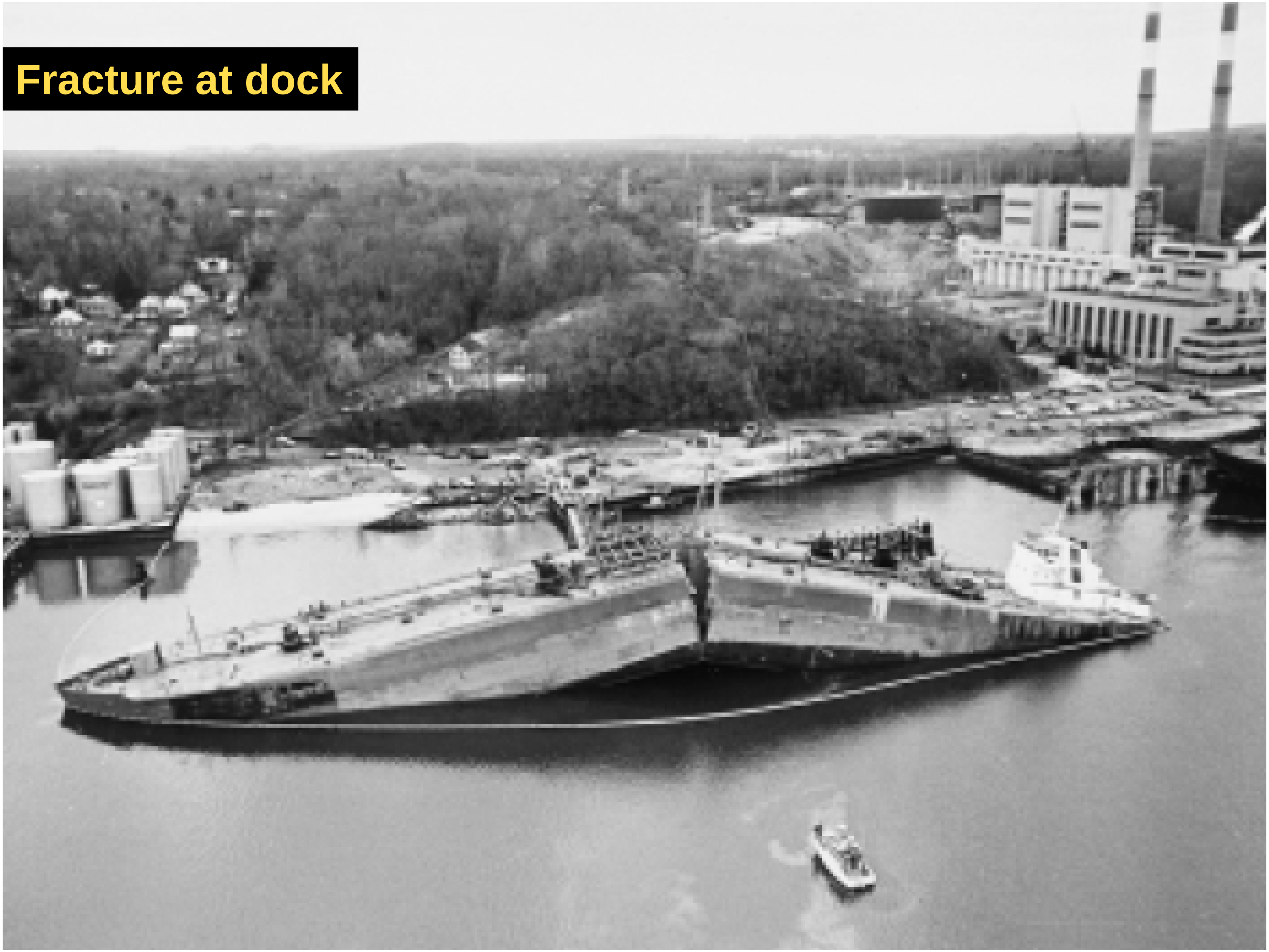
- 2580 Liberty ships
- 414 Victory ships
- 530 T2 oil tankers

Towards the end of the program one ship was completed in less than five days.

# Between 1942 and 1952:

- 250 large welded steel ships were lost
- Another 1200 welded ships suffered relatively minor damage (cracks less than 3 m long)


# Fracture at sea


Fracture at dock


Fracture at dock

# Over 58 cases of non-ship failures had been reported

- Storage tanks and pressure vessels
- Offshore structures
- Bridges
- Pipe lines
- …

Floating roof tank, Esso Fawley Refinery,1952

# What is the problem?

| Year | Structure | Temp at failure / °C | Steel thickness / mm | Age of structure / years |
|---|---|---|---|---|
| 1904 | Water tank | 0 | 15.9 | 7 |
| 1925 | Oil storage tank | -20 | 25.4 | - |
| 1940 | Trussed bridge | -14 | 52 | 2-3 |
| 1943 | Liberty ships | 2 | - | ≤1 |
| 1951 | Plate grider bridge | -1 | 63 | 3 |
| 1952 | Oil/gas storage tank | 8 | 27 | - |
| 1954 | Post office building | 1 | 15-25 | 0 |

?

Rivet or weld?

# Please wait…

# Properties of materials

- Mechanical properties → 
- Electrical properties
- Magnetic properties
- Optical properties
- Corrosion properties
- Biological properties
- …

tension test

compression test

impact test

hardness test

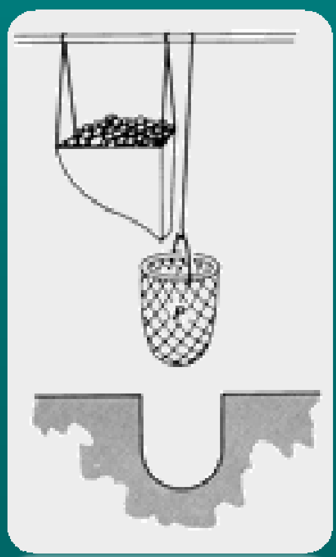
creep test

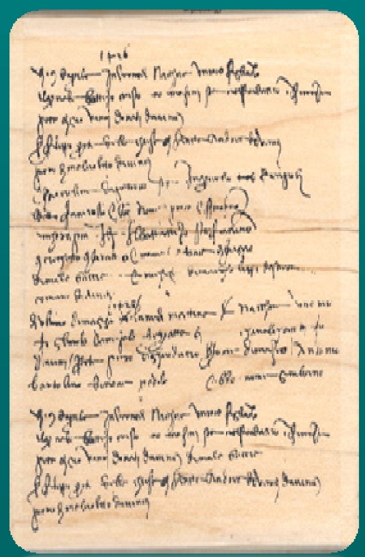
…

# Tension test

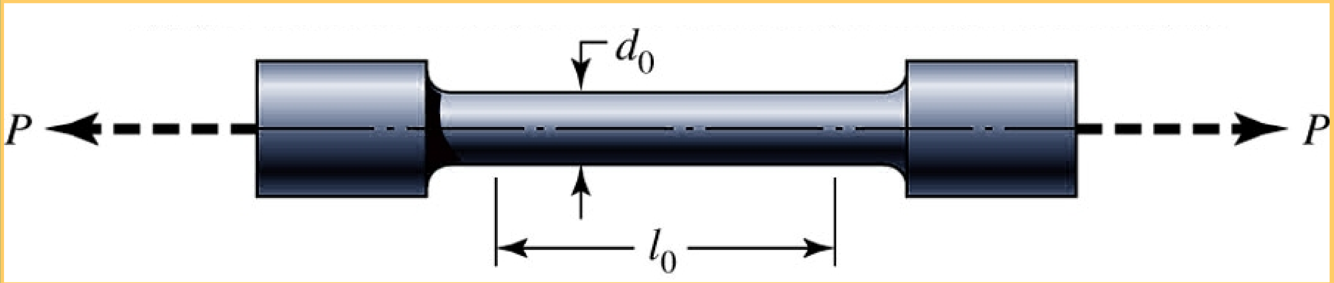
- Leonardo Da Vinci,1495 (500 yrs ago!) observed:

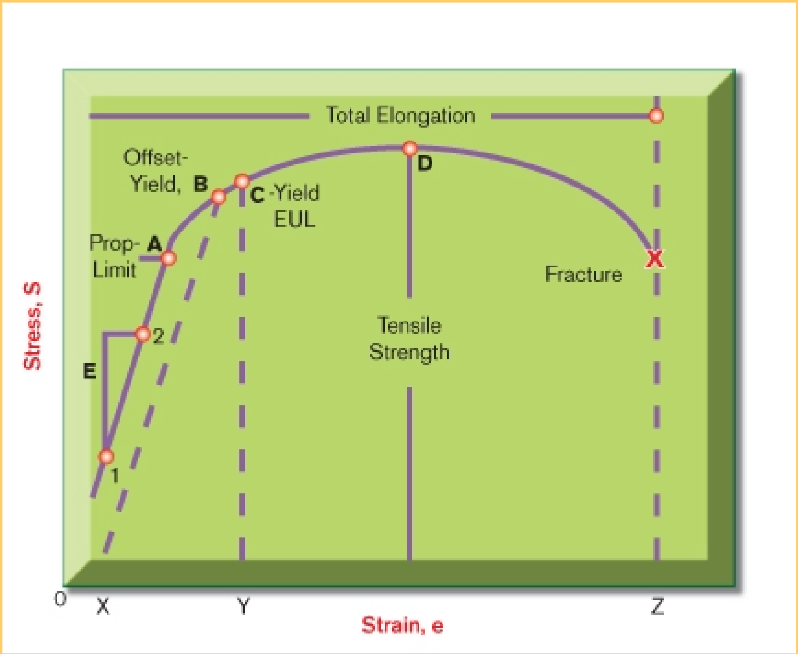
  the longer the wire, the smaller the load for failure
- Reasons:
  - flaws cause premature failure
  - Larger samples contain more flaws!



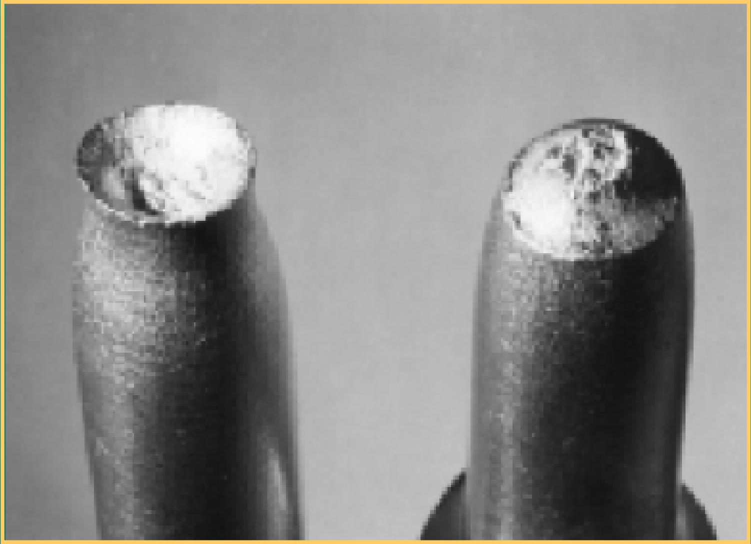


# Tension test (static material test)



# Fracture type

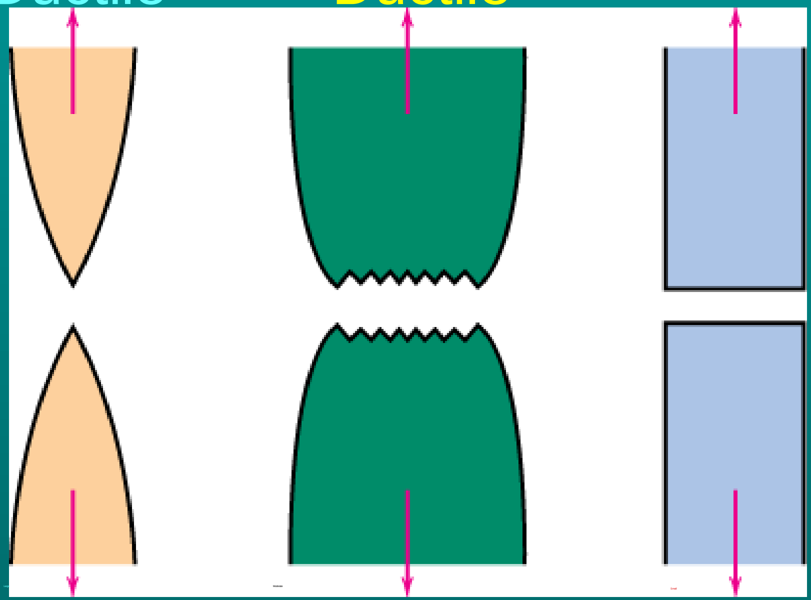


Ductile fracture (cup-and-cone)

Brittle fracture

# Ductile fracture is desirable!

Very Ductile | Moderately Ductile | Brittle

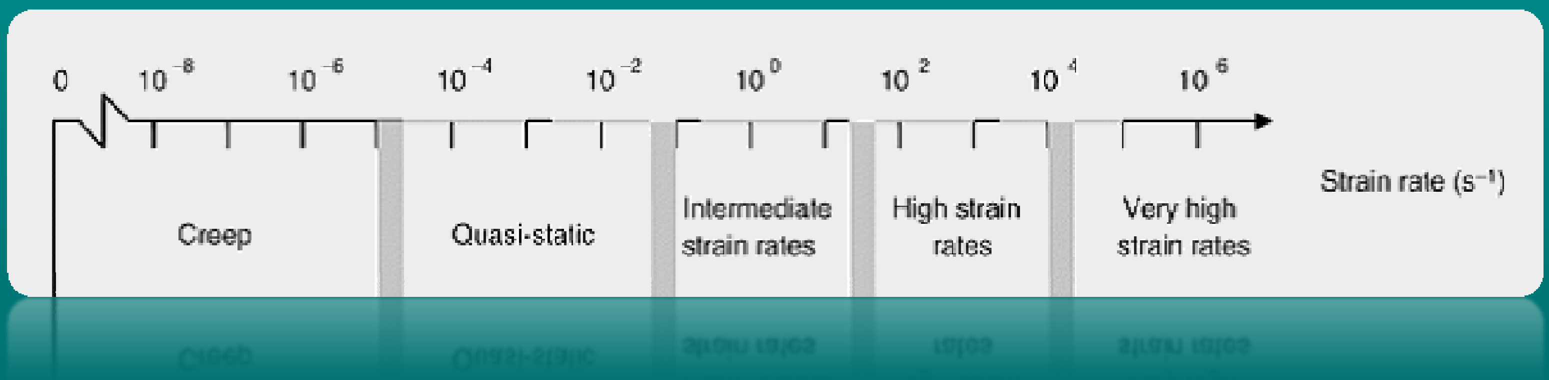


Ductile:
warning before fracture

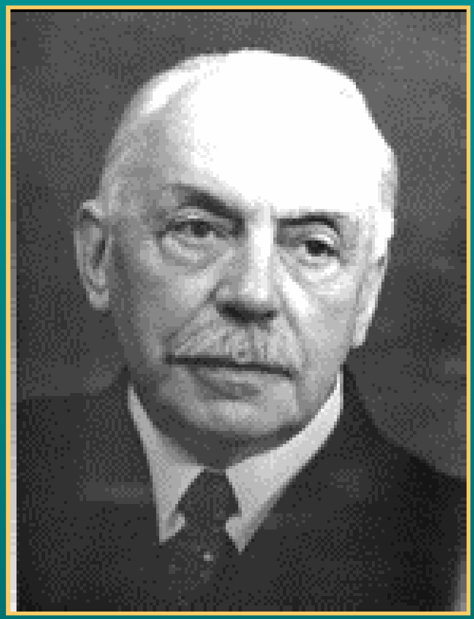
Brittle:
No warning

# Loading

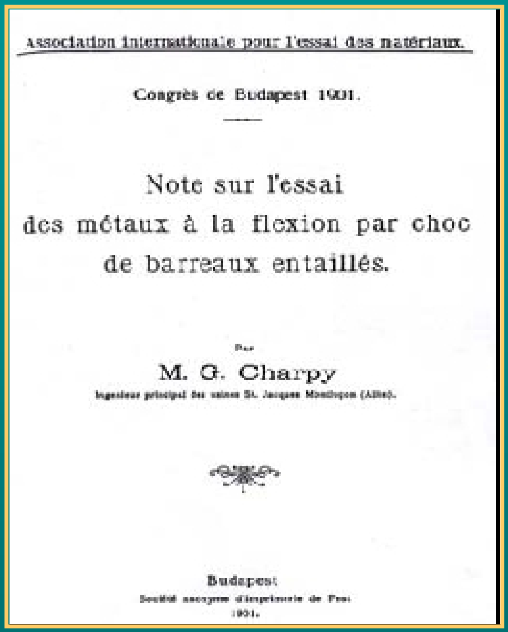
- Static loading (Low strain rate) $10^{-1} – 10^{-5}$ ($S^{-1}$)
- Dynamic loading (High strain rate) $10^{+x}$ ($S^{-1}$)



# Impact test (dynamic material test)



Augustin Georges Albert Charpy
(1865 – 1945 ), Paris



Association internationale pour l'essai des matériaux.

Congrès de Budapest 1901.

Note sur l'essai
des métaux à la flexion par choc
de barreaux entaillés.

Par

M. G. Charpy

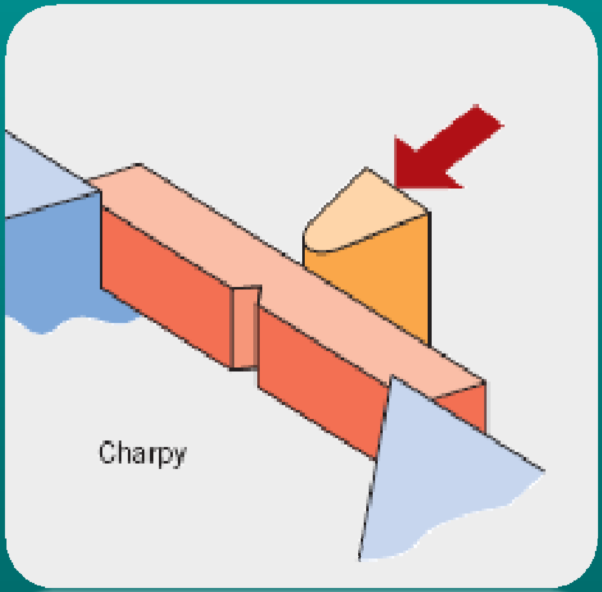
Budapest

1901.

Title page of Charpy's paper
at the VIIth Congress of the International Assoc. For Testing of Materials in Budapest, 1901

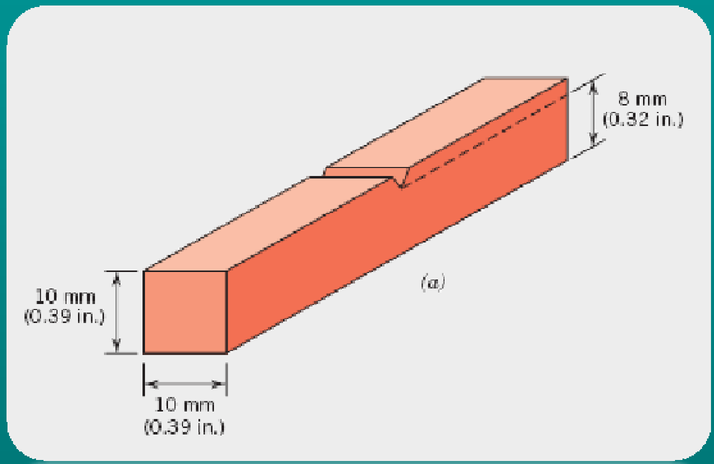
# Charpy impact test

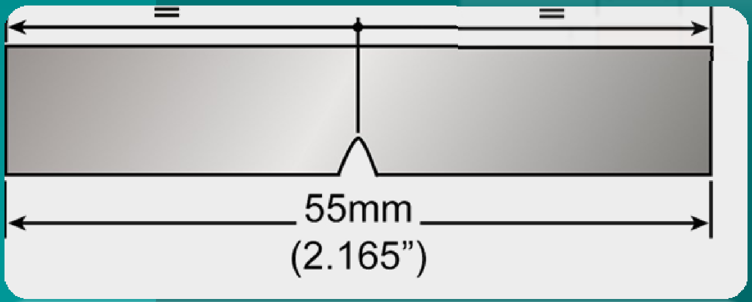
- ASTM E 23
- Impact test velocity is ~ 5 m/s

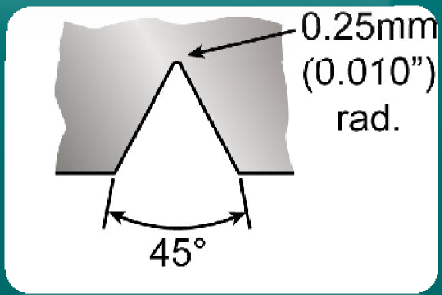


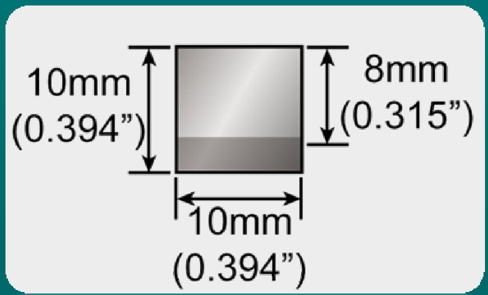
# Impact test machine

# Charpy V-notch impact test specimen

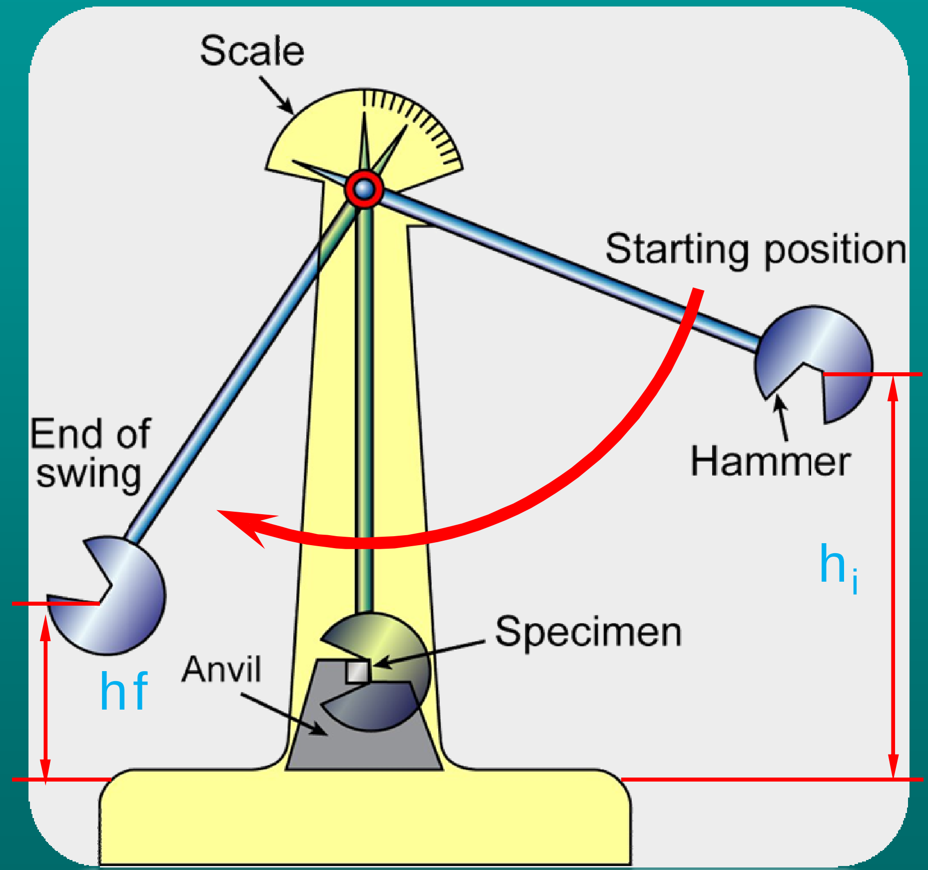


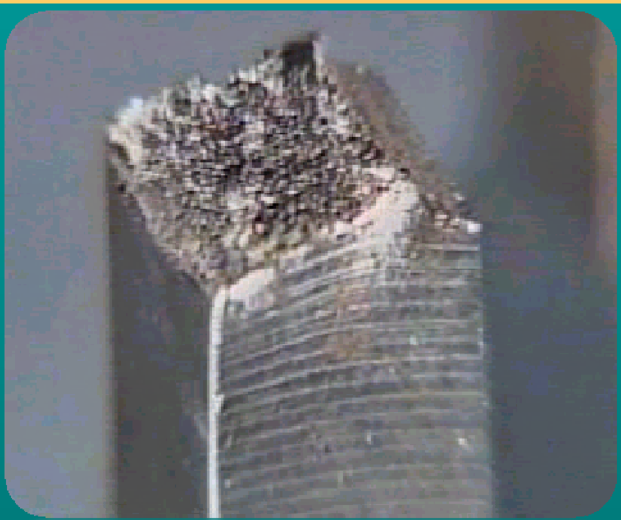
# Charpy V-notch impact test



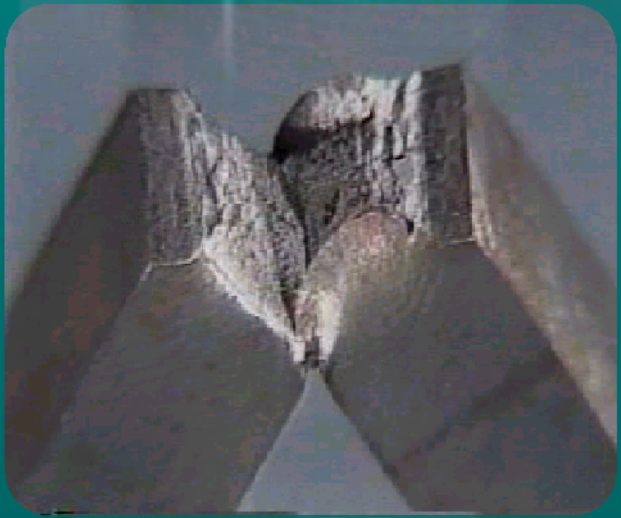

**Fracture energy = $mgh_i - mgh_f$**

# Charpy impact test

100% Brittle

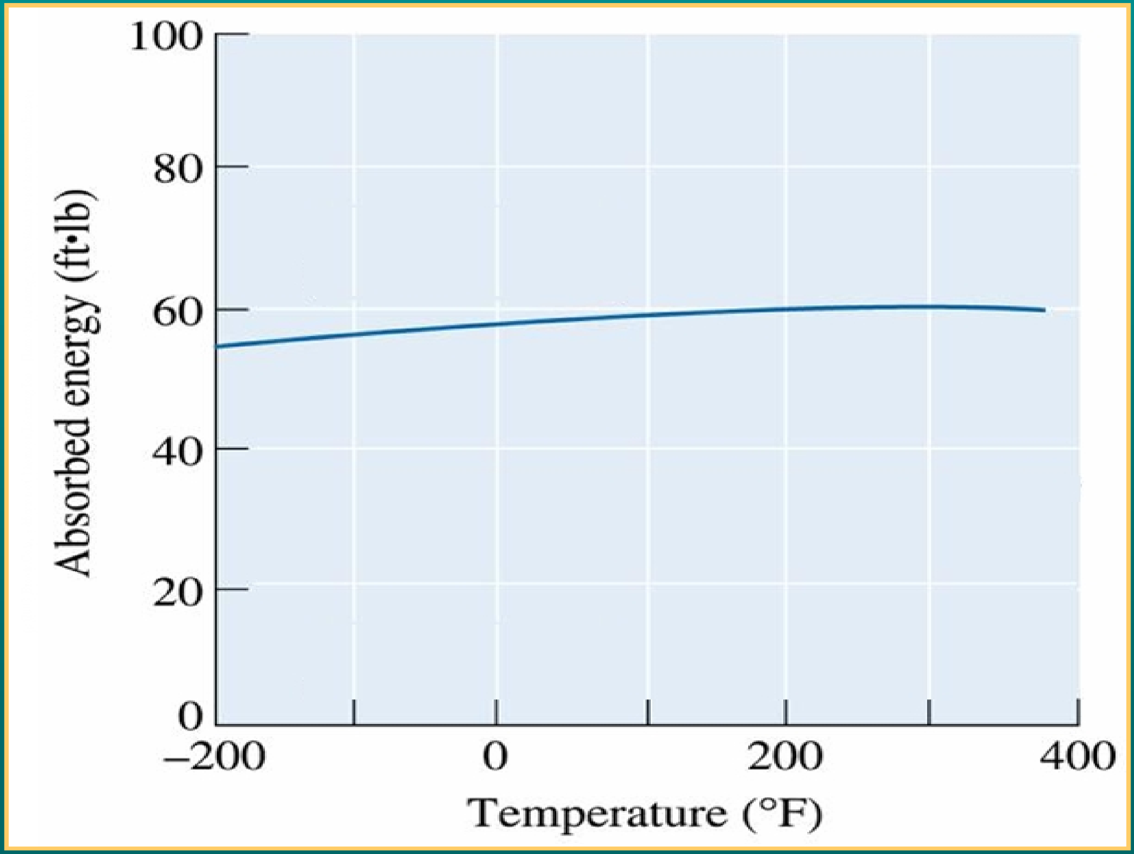


100% Ductile



# Impact test graph

- More absorbed energy à More ductility



# Let’s get back to our story!

How can I find the answer ?

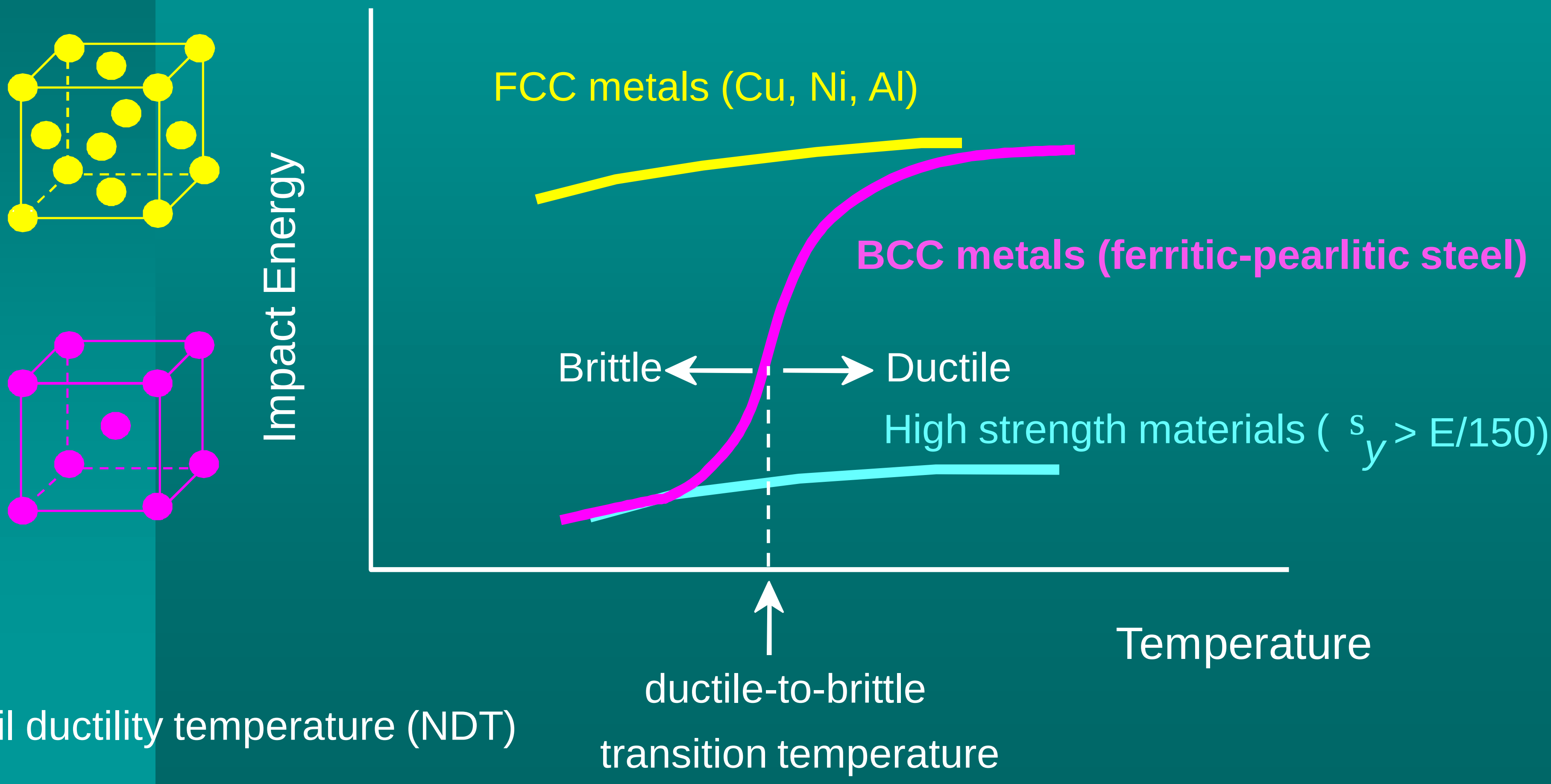
# A broad research program

- To find the causes of this failures
- Gaining a better understanding of the mechanism of brittle fracture and fracture in general

# The U.S. National Bureau of Standards' report (Williams et al. 1948)

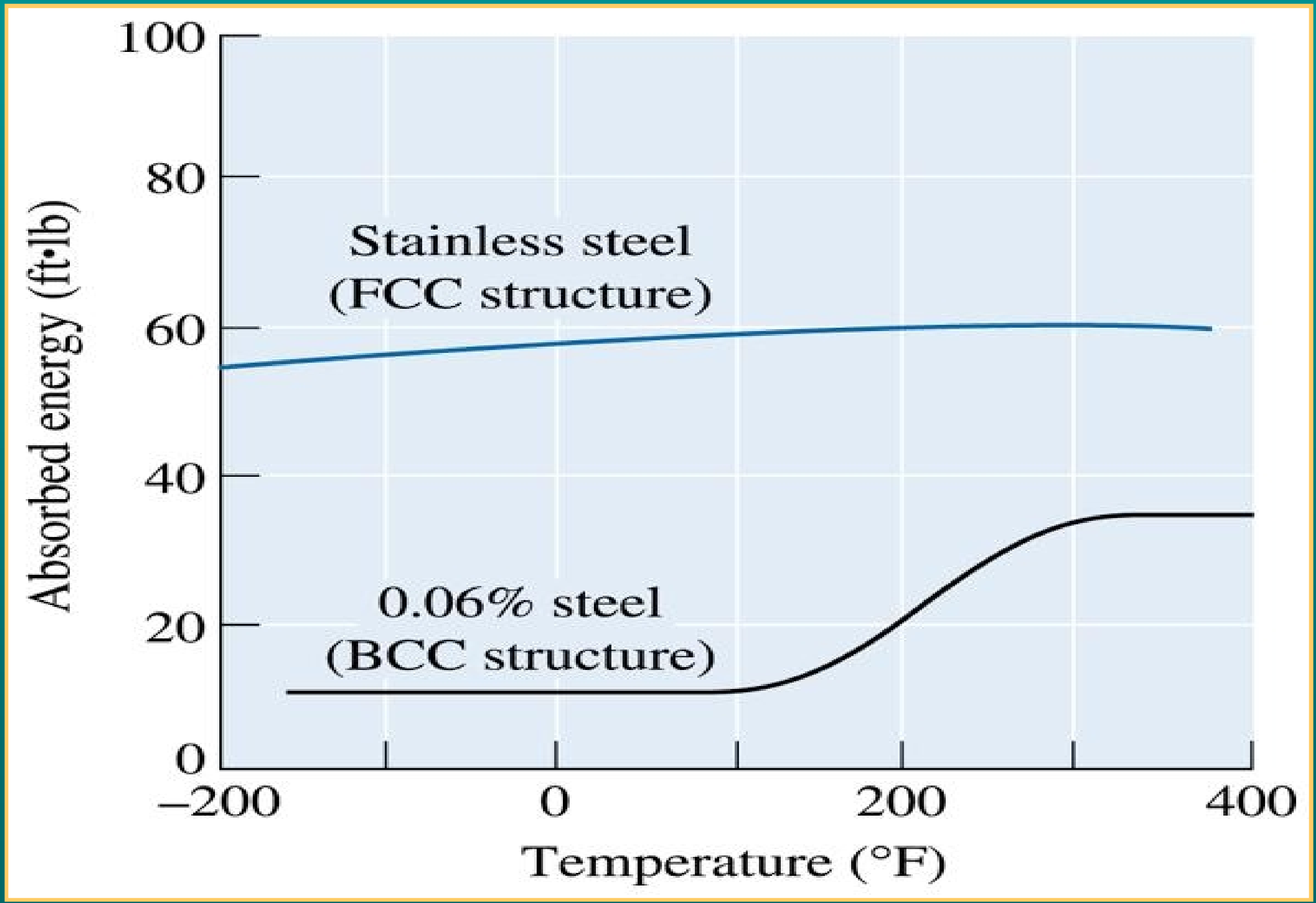
- The NBS study included:
  - Chemical analysis
  - Tensile tests
  - Microscopic examination
  - Charpy impact tests
- The Notable conclusions of the report:
  - The plates in which the fracture arrested had consistently higher impact energies and lower transition temperatures than those in which the fractures originated.
  - There was no similar correlation with chemical composition, tensile properties or microstructure

# Ductile-to-Brittle Transition Temperature (DBTT)...

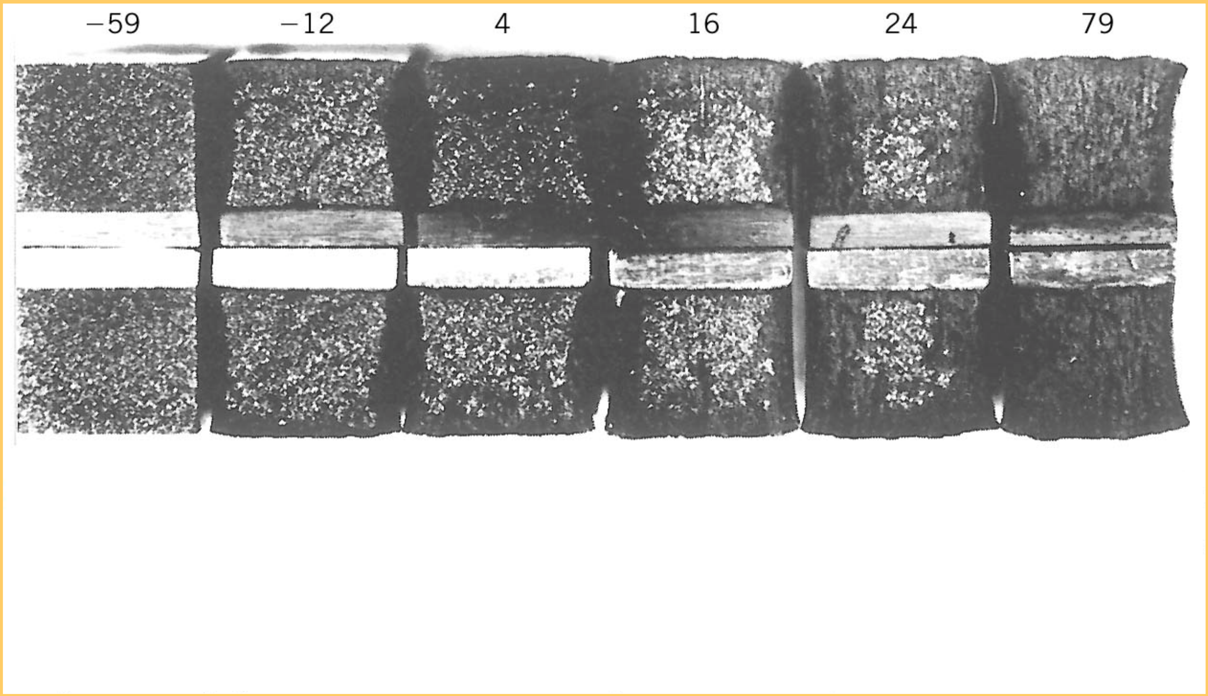



Nil ductility temperature (NDT)

# Some examples…



# Fracture surface

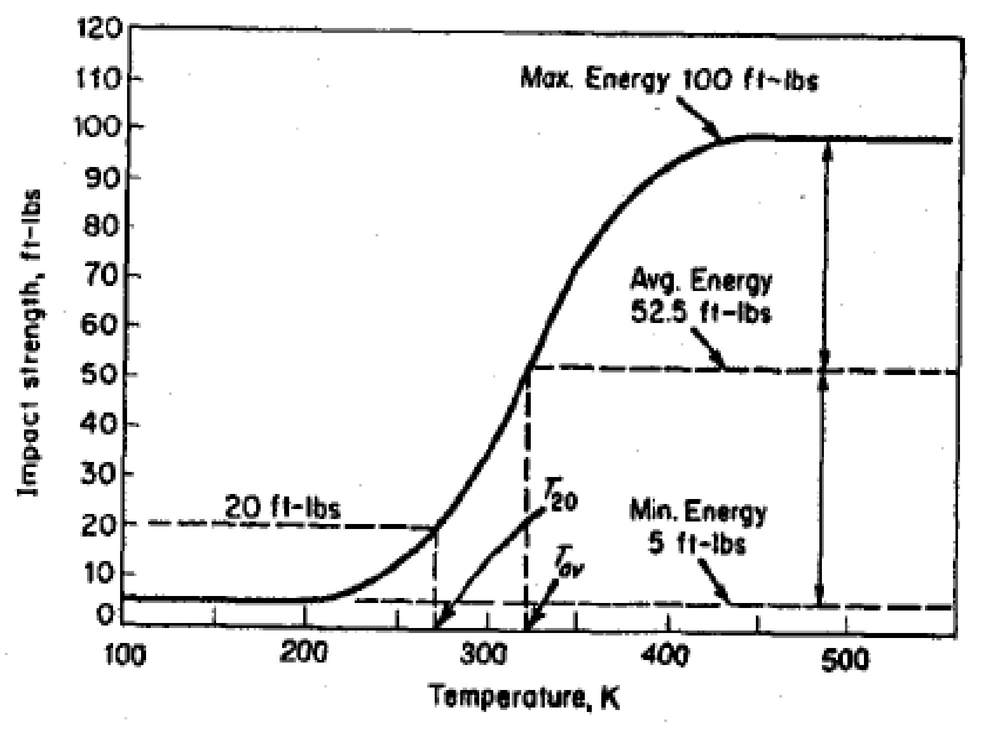



fracture surfaces of A36 steel Charpy V-notch specimens tested at indicated temperatures (in °C).

# Criterion for transition temperature

- Ductility transition temperature ($T_{20}$ in the figure)
- Average temperature ($T_{av}$ in the figure)

**1ft-lb = 1.4 J**

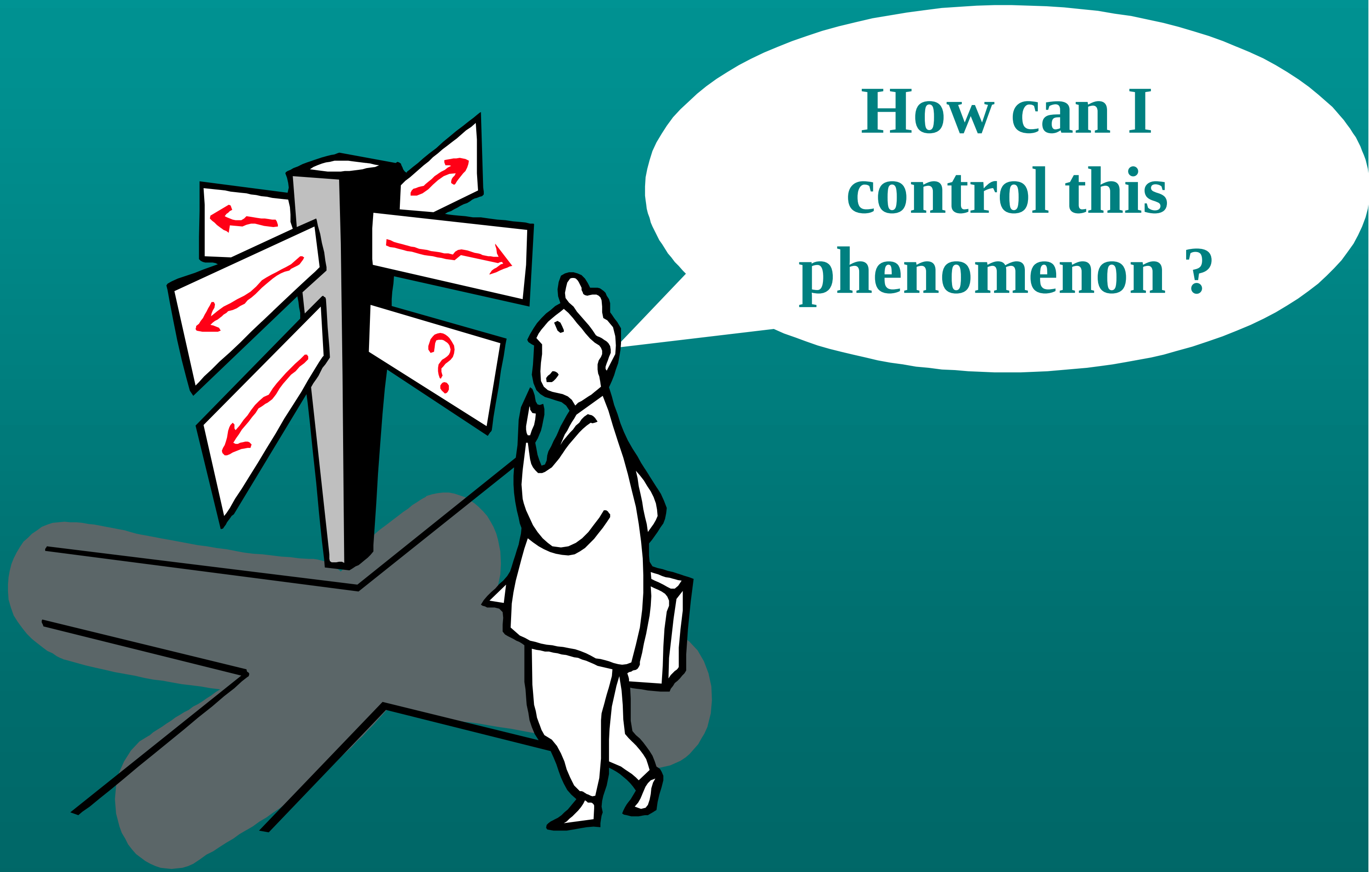


# Why?

- In FCC metals, the flow stress, i.e. the force required to move dislocations, is not strongly temperature dependent. Therefore, dislocation movement remains high even at low temperatures and the material remains relatively ductile
- The yield stress or critical resolved shear stress of BCC crystals is markedly temperature dependent, in particular at low temperatures
- The temperature sensitivity of the yield stress of BCC crystals has been attributed to the presence of interstitial impurities on the one hand, and to a temperature dependent Peierls-Nabarro force on the other


$CO_2$ cylinder

# Ductile-to-brittle transition



# Metallurgical factors affecting transition temperature

Changes in transition temperature of over 50 °C can be produced by changes in :

- Chemical composition
- Microstructure
- Heat treatment

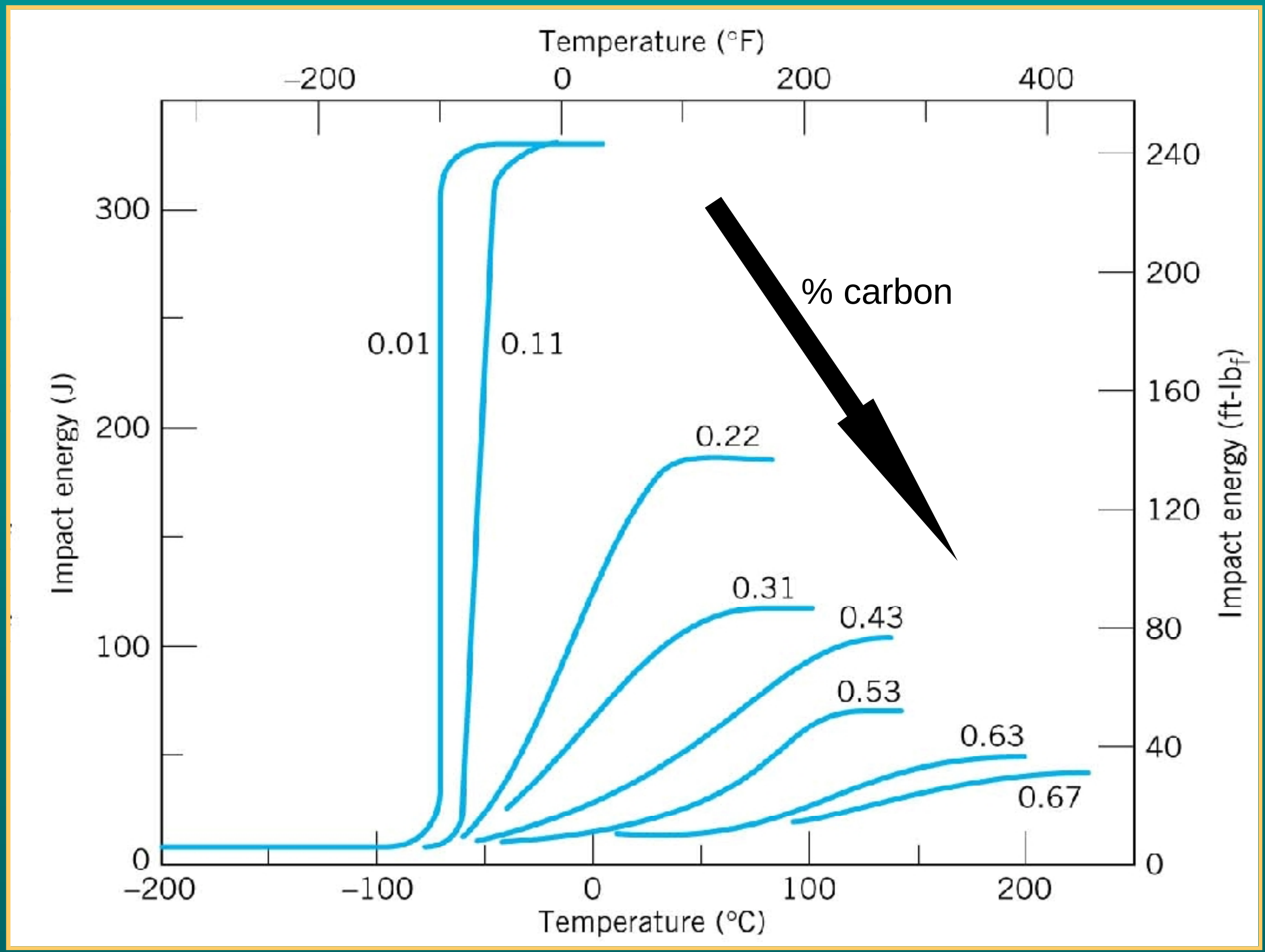
# Effect of chemical composition

- The largest changes result from changes in the amount of carbon and manganese.

0.1% C ↑ 14 °C ↑ DBTT

0.1% Mn ↑ 5 °C ↓ DBTT

# Effect of carbon



# Note that…

- The Mn:C ratio should be at least 3:1 for satisfactory notch toughness
- A higher Mn:S ratio reduces the ductile-brittle transition temperature substantially

- When the oxygen content was raised from 0.001% to the high value of 0.057%, the transition temperature was raised from -15 °C to 340 °C !!
- In view of this results, it is not surprising that deoxidation practice has an important effect.

# Type of steels

- Rimmed steel , with its high iron oxide content, generally shows a transition temperature above room temperature
- Semikilled steels, which are deoxidized with Si, have a lower transition temperature
- For steels which are fully killed with Si + Al the ductility transition temperature will be -60 °C

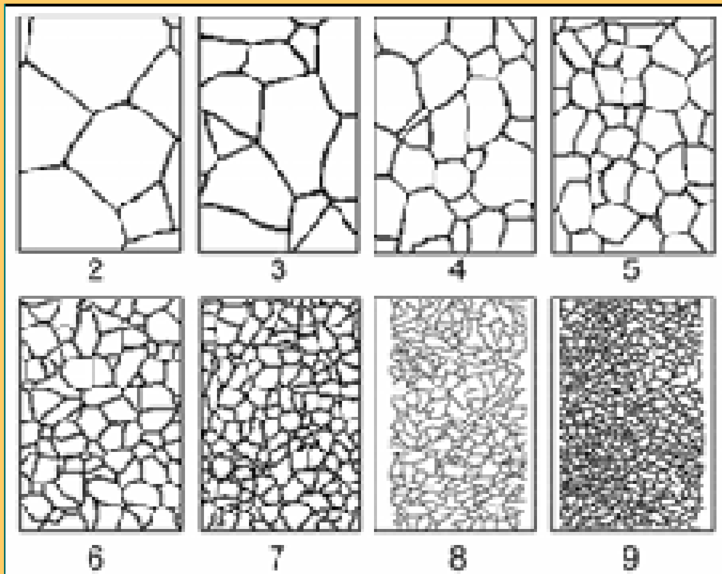
# Effect of other elements

| | | | | |
|---|---|---|---|---|
| 0.01% P | ↑ | 7 °C | ↑ | DBTT |
| 1% Ni | ↑ | 10 °C | ↓ | DBTT |

- The role of nitrogen is difficult to asses because of its interaction with other elements but generally considered to be detrimental.
- Silicon > 0.25% raise the transition temperature.
- Molybdenum raises the transition temperature almost as rapidly as carbon.
- The transition temperature decreases about 40 °C per 0.1% aluminum added. However, additions of aluminum greater than that required to tie up the nitrogen have little effect.

# Effect of microstructure

- Grain size has a strong effect. An increase of one ASTM number (actually a decrease in grain diameter) can result in a decrease in transition temperature of 15 °C for mild steel.



ASTM grain sizes, 100X magnification

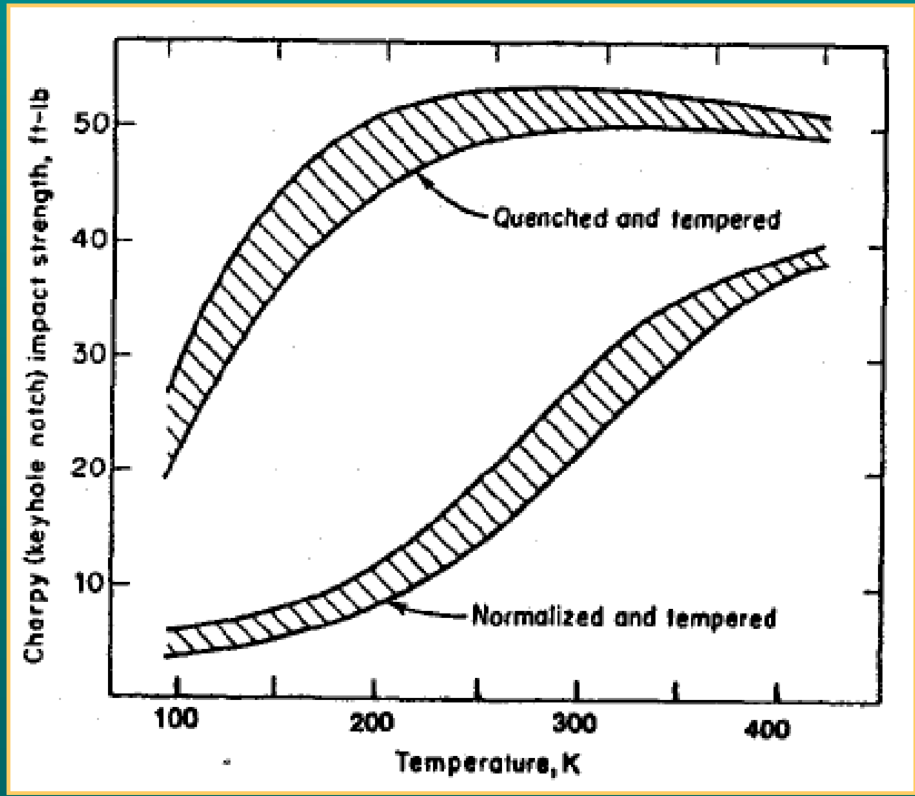
| ASTM Grain Size Number | Number of Grains per Square Inch at 100X | Average Grain Diameter ($10^{-6}$m) |
|---|---|---|
| 1 | 1 | 254 |
| 2 | 2 | 180 |
| 3 | 4 | 127 |
| 4 | 8 | 90 |
| 5 | 16 | 64 |
| 6 | 32 | 45 |
| 7 | 64 | 32 |
| 8 | 128 | 22.4 |
| 9 | 256 | 15.9 |
| 10 | 512 | 11.2 |

ASTM E 112

Blue line ~ grain of salt size
Red line~ diameter of human hair

# Effect of Heat Treatment

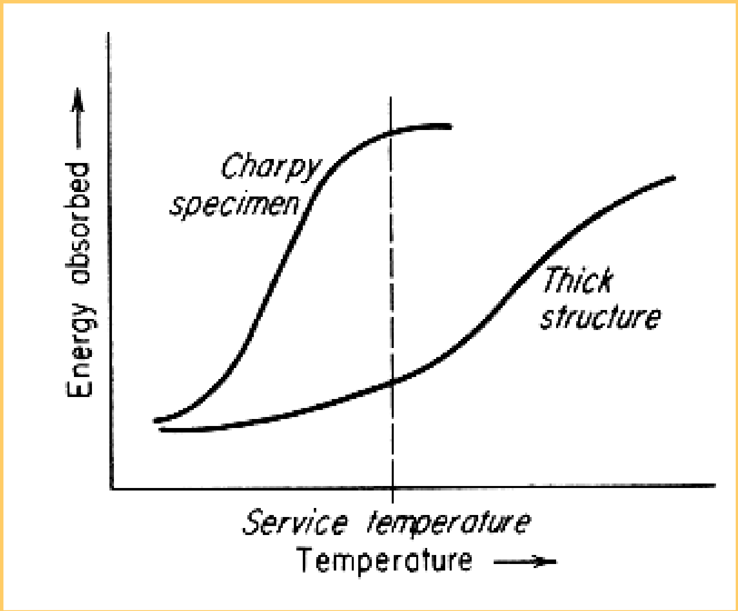
- Heat treatment, through its influence on microstructure, has a strong effect on impact properties.




Both heat treatments produce the same hardness but widely different DBTT

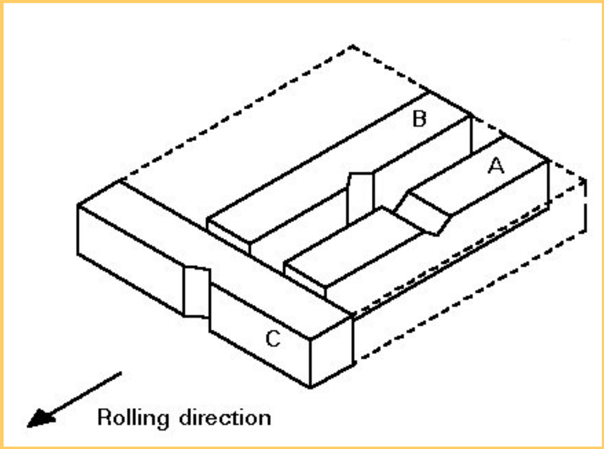
# Other factors affecting transition temperature

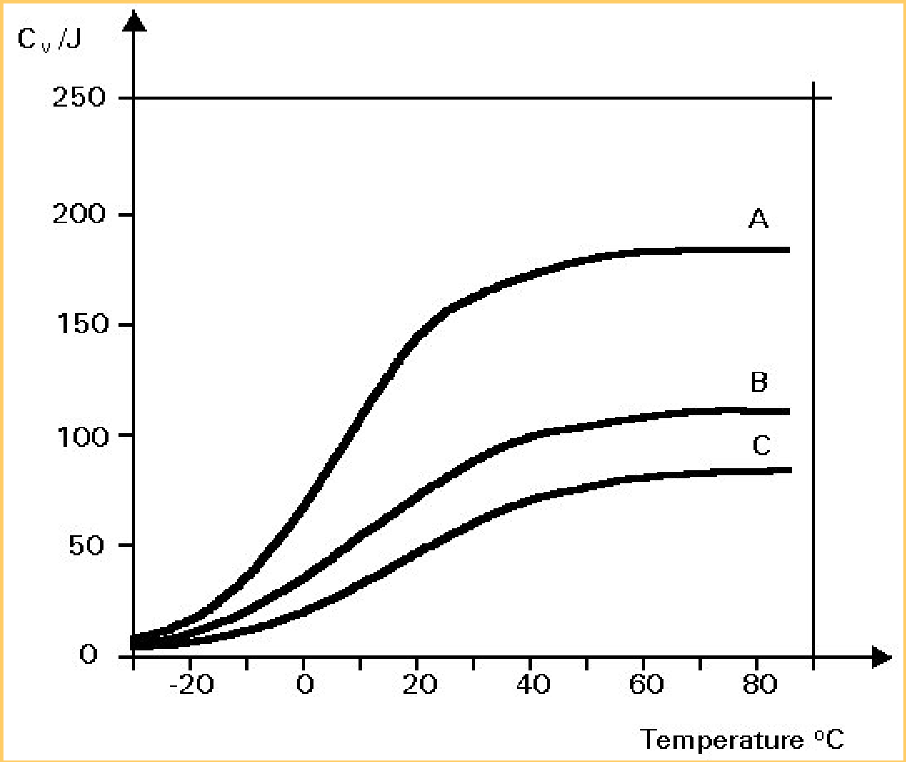
- For a given chemical composition and deoxidation practice, the transition temperature will be appreciably higher in thick hot-rolled plates than in thin plates ( t > 13 mm). This is due to the difficulty of obtaining uniformly fine pearlite and grain size in a thick section.



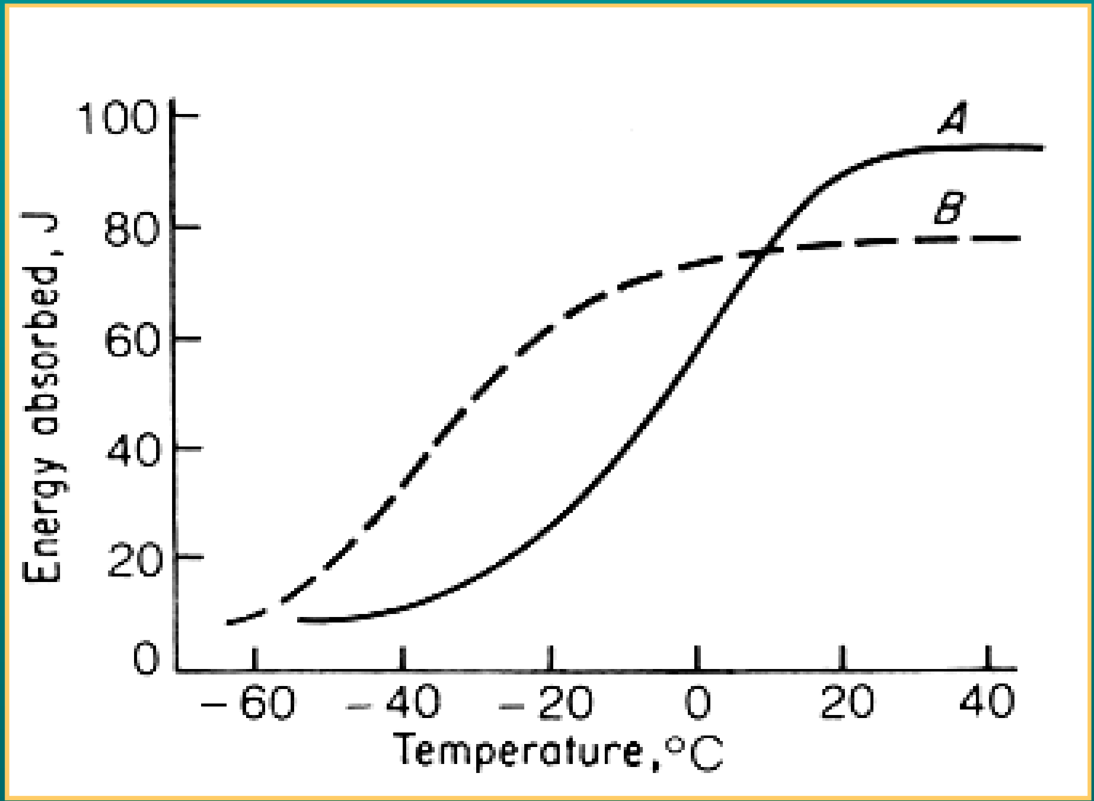
# Other factors affecting transition temperature

- The notched-impact properties of rolled or forged products vary with orientation in the plate or bar.



# Error in judgment?




Transition temperature curve for two steels showing fallacy of depending on room temperature results.

# RMS Titanic: Did a metallurgical failure cause a night to remember?

The bow of the Titanic as it appeared during 1986 expedition

# Chemical analysis

- Comparing the composition of the Titanic steel and ASTM A36 steel shows that the modern steel has a higher manganese content and lower sulfur content, yielding a higher Mn:S ratio that reduced the ductile-brittle transition temperature substantially. In addition, ASTM A36 steel has a substantially lower phosphorus content, which will also lower the ductile-to-brittle transition temperature.

Table II. The Composition of Steels from the *Titanic*, a Lock Gate, and ASTM A36 Steel

| | C | Mn | P | S | Si | Cu | O | N | MnS: Ratio |
|---|---|---|---|---|---|---|---|---|---|
| *Titanic* Hull Plate | 0.21 | 0.47 | 0.045 | 0.069 | 0.017 | 0.024 | 0.013 | 0.0035 | 6.8:1 |
| Lock Gate* | 0.25 | 0.52 | 0.01 | 0.03 | 0.02 | — | 0.018 | 0.0035 | 17.3:1 |
| ASTM A36 | 0.20 | 0.55 | 0.012 | 0.037 | 0.007 | 0.01 | 0.079 | 0.0032 | 14.9:1 |

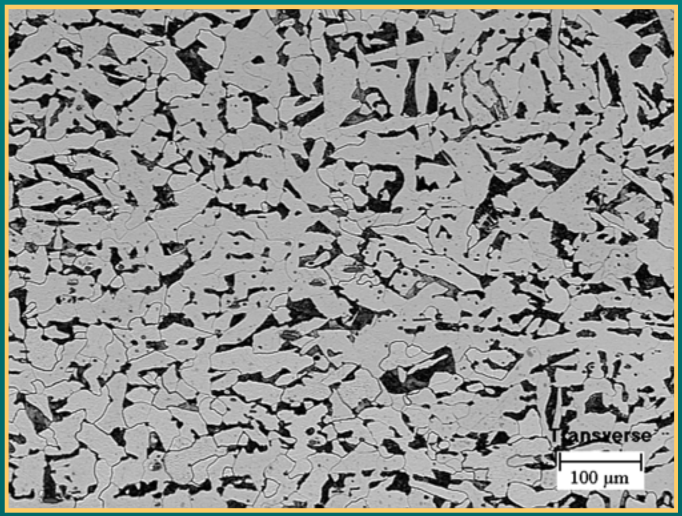
*Steel from a lock gate at the Chittenden ship lock between Lake Washington and Puget Sound, Seattle, Washington.

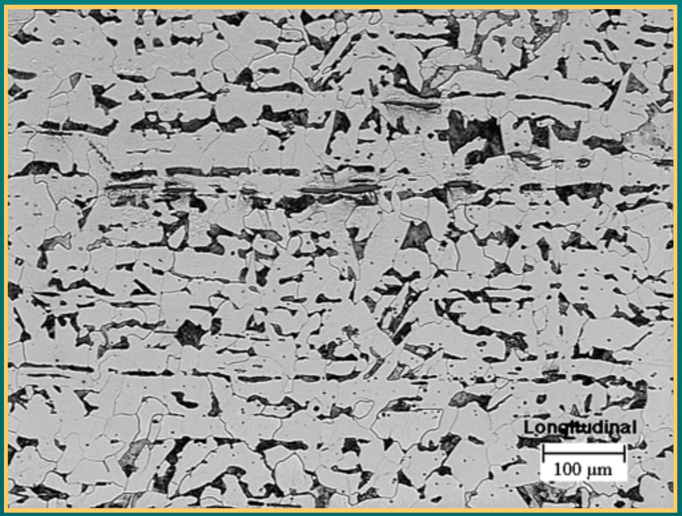
# Tension test

| Table III. A Comparison of Tensile Testing of *Titanic* Steel and SAE 1020 | | |
|---|---|---|
| | ***Titanic*** | **SAE 1020** |
| **Yield Strength** | 193.1 MPa | 206.9 MPa |
| **Tensile Strength** | 417.1 MPa | 379.2 MPa |
| **Elongation** | 29% | 26% |
| **Reduction in Area** | 57.1% | 50% |

# Metallography

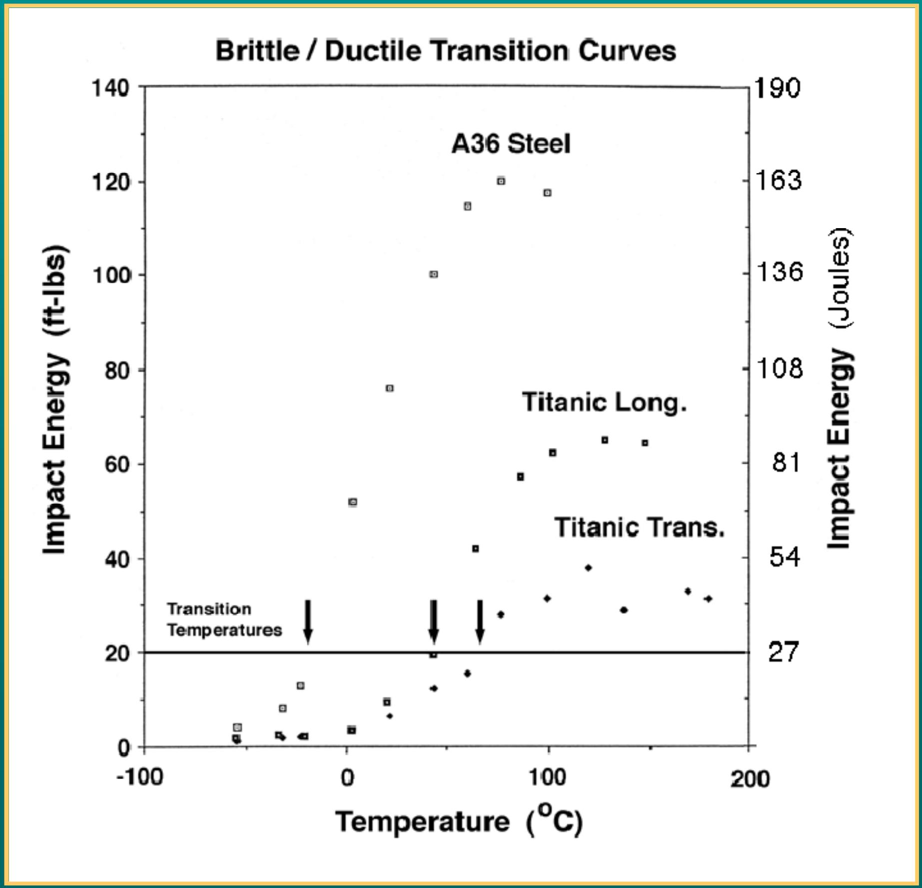
- An optical micrograph of steel for the hull of the Titanic in (right) longitudinal and (left) transverse directions, showing banding that resulted in elongated pearlite colonies and MnS particles. Etchant is 2% Nital.



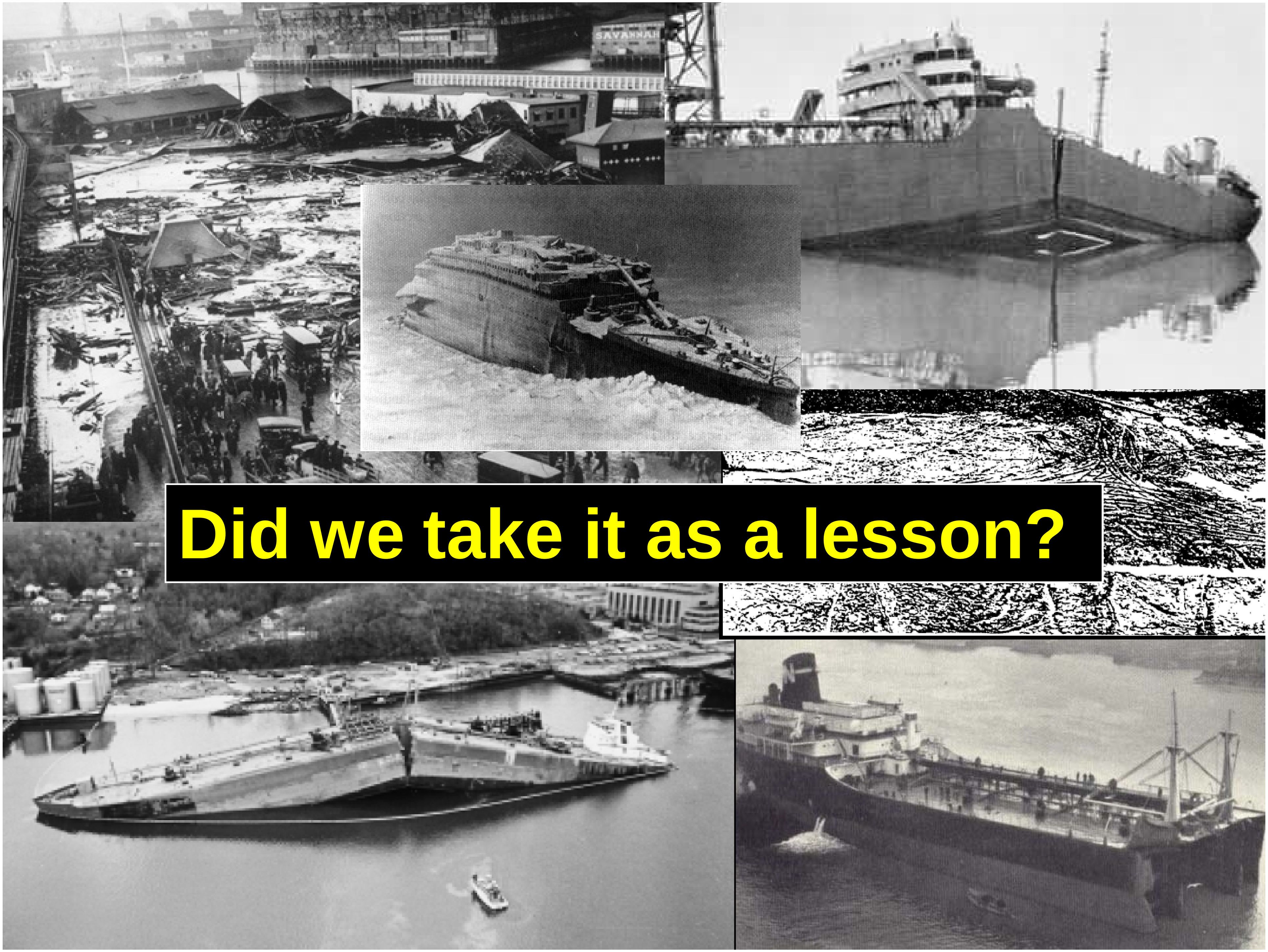
# DBTT

- The ductile-brittle transition temperature for the longitudinal specimens was 33°C.



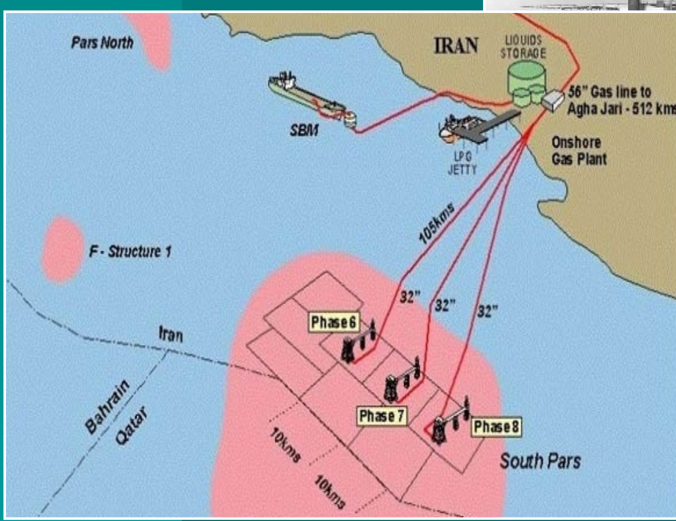
# Conclusions

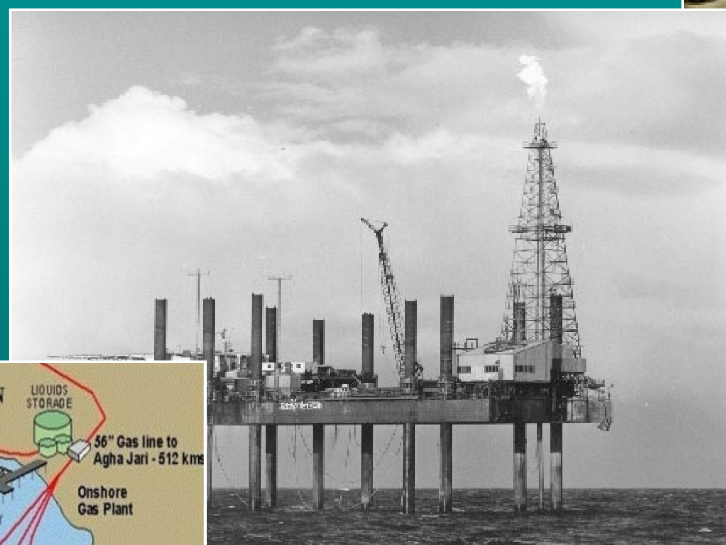
- The steel used to construct the Titanic's hull, though adequate in strength, possessed a high DBTT (at the time of the collision, the sea water temp. was -2 °C)
- The low toughness was likely due to a complex combination of factors, including low Mn content, a low Mn:C ratio, a large ferrite grain size and large and coarse pearlite colonies.
- The steel used was probably the best plain carbon ship plate available at the time of the ship's construction.


Did we take it as a lesson?

- Did we take it as a lesson?

**South of Iran**



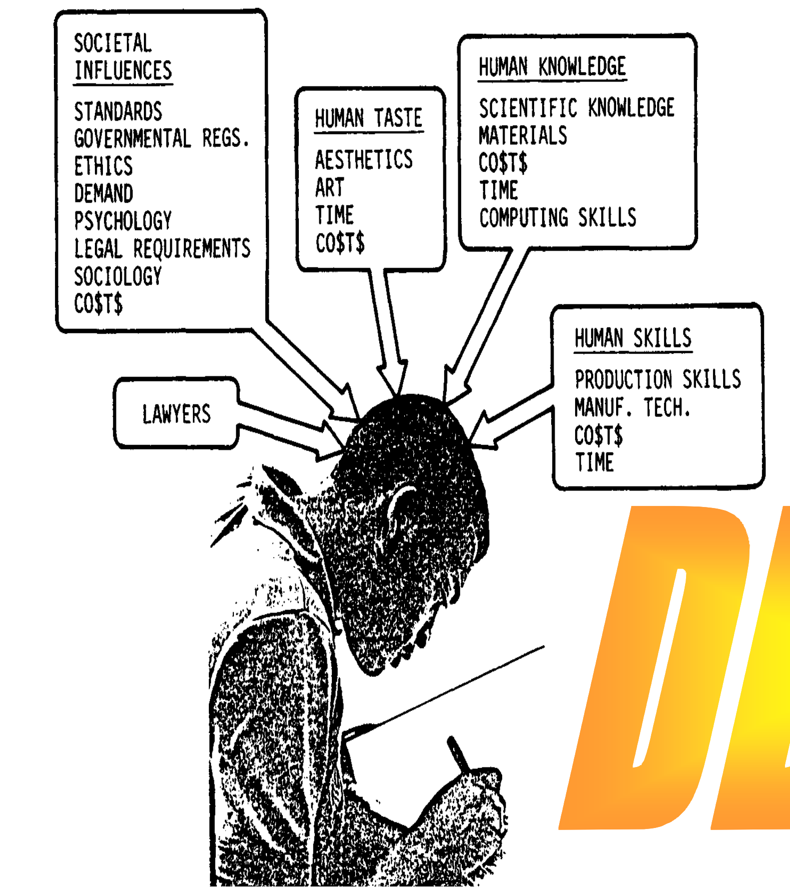



**Offshore drilling rig, “Sea Gem”, December 27, 1964**

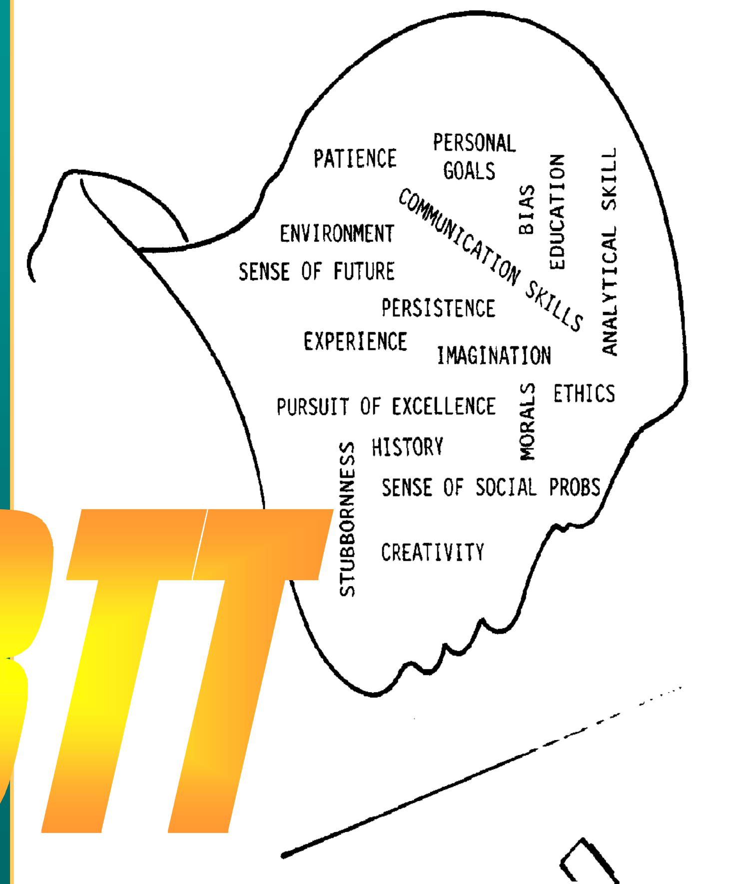
**Robert Jenkins pressure vessel, November 6, 1970**


CORSAIR
DANGER IS EVERYWHERE
DESIGN STRATEGY: STAY ABOVE THE DBTT!

# I hope…




External influences on the engineering designer.




Internal influences on the engineering designer.

DBTT

Thanks for your attention