Image Cover Sheet

CLASSIFICATION	SYSTEM NUMBER
UNCLASSIFIED	511877

TITLE

Materials Selection for U.S. Navy Ships

System Number:

Patron Number:

Requester:

Notes: Paper # 3 contained in Parent sysnum #511874

DSIS Use only:

Deliver to: BA

Materials Selection for U.S. Navy Ships

by P.W. Holsberg and E.J. Czyryca

Carderock Division, Naval Surface Warfare Center
9500 West Bethesda, MD 20817

ABSTRACT

Over the past several years the U.S. Navy has formally implemented its metallic materials selection process (MSP). The MSP provides guidance for the design agent for selection of materials for critical, non-nuclear applications. It further requires the design agent to document all information used in the selection process. In critical applications, a fracture toughness review process (FTRP) is invoked, where all material properties required for fitness for service over the life of the ship are defined, determined and/or documented. A metallic materials properties database (MMPD) is now being established to be available to aid in the processes. Details of each process and their relationship with each other and the database are discussed.

MATERIALS SELECTION FOR U.S. NAVY SHIPS

by
Paul W. Holsberg, NSWCCD Code 61
Ernest J. Czyryca, NSWCCD Code 614

Presented at
8th CF/CRAD on NAVAL APPLICATIONS OF MATERIALS TECHNOLOGY
11 May 1999

MATERIAL SELECTION REQUIREMENTS

- **METALLIC MATERIAL SELECTION REQUIREMENTS**

- **Provides guidance and direction for the design agent to select materials for use in critical, non-nuclear applications**
- **Requires design agent to document Material Selection Information (MSI) for critical applications**

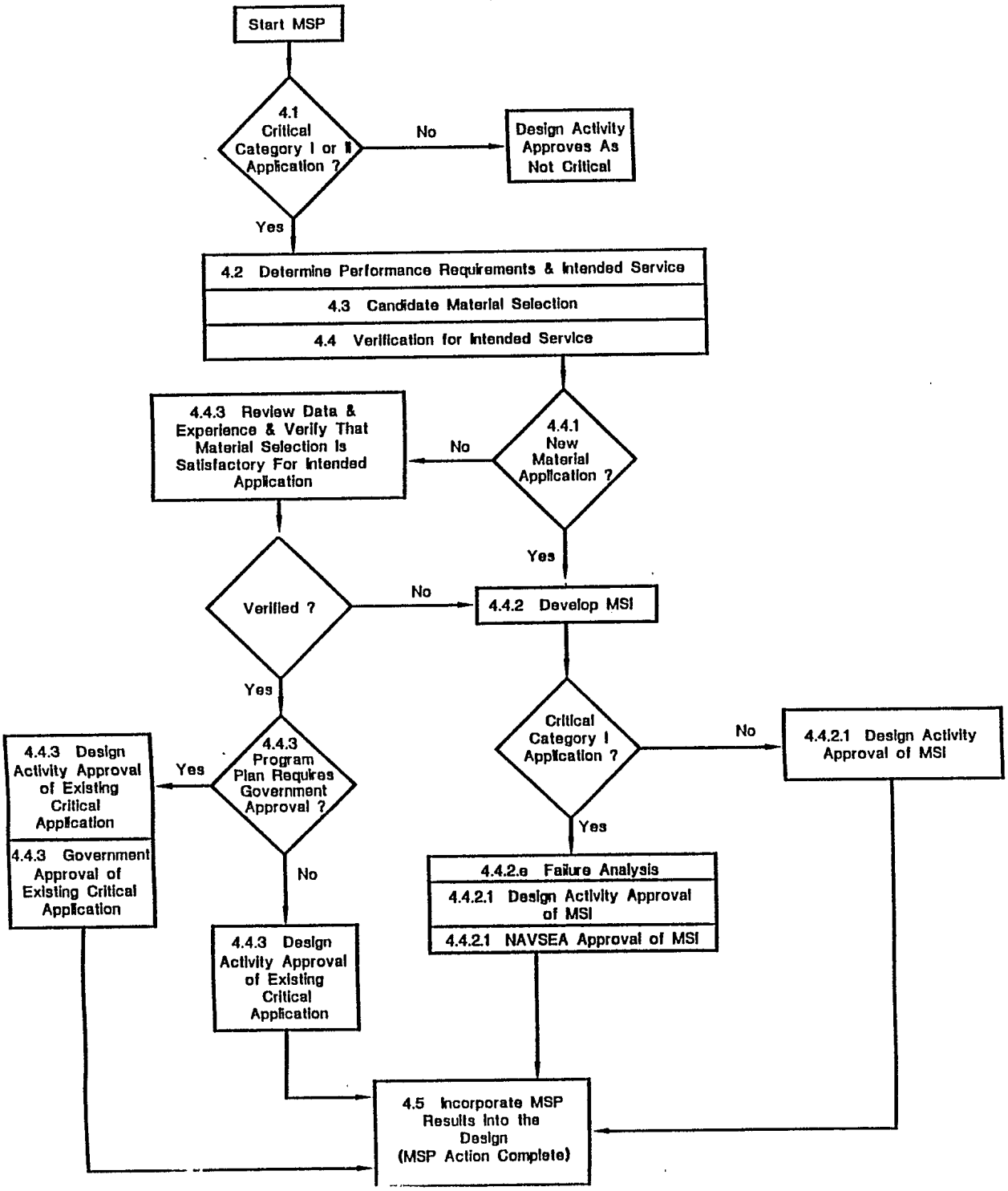
MATERIAL SELECTION REQUIREMENTS

- **ESTABLISH CRITICALITY OF APPLICATION**
- **Category I - Loss of Life, Ship, or Primary Mission**
- **Category II - Severe Personal Injury, Loss of Secondary Mission, Weight Handling Equipment Failure, or Replacement Cost Exceeds $1M per Ship**

MATERIAL SELECTION REQUIREMENTS

- **IF CRITICAL, DESIGN AGENT DOCUMENTS MATERIAL SELECTION INFORMATION (MSI) FOR CANDIDATE MATERIAL**
- **Category I - Needs NAVSEA approval for MSI**
- **Category II - Design Agent's Senior Design Manager approves MSI**

MATERIAL SELECTION PROCESS



MATERIAL CHARACTERISTICS

- **MATERIAL PROPERTIES - Strength, toughness, damping, physical properties, frictional properties, fatigue strength, creep and stress relaxation, cavitation resistance, toxic effects**

- **DESIGN CRITERIA - Some existing designs are alloy system specific. The validity for new alloy systems must be justified.**

MATERIAL CHARACTERISTICS

- **IN-SERVICE VARIABLES - Expected operational environmental factors, life expectancy, ballistic and shock properties, fire effects, material degradation (corrosion and temperature)**

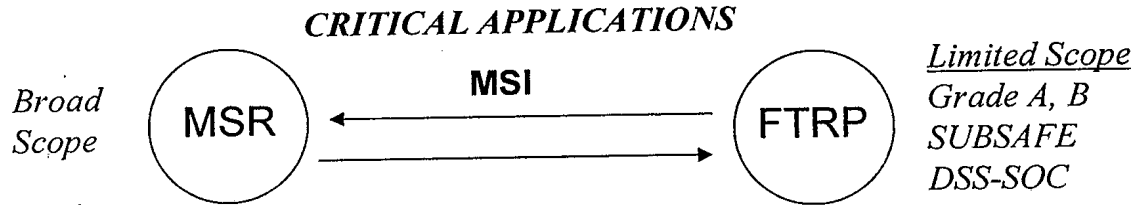
- **MANUFACTURING PROCESSES - Welding, brazing, hot and cold forming, peening, coating, cladding, inspectability, availability, fabrication requirements and effects**
- **LIFE CYCLE COSTS**

MATERIAL SELECTION REQUIREMENTS

- **ADJUNCTS**

- **FRACTURE TOUGHNESS REVIEW PROCESS (FTRP)**
- **METALLIC MATERIALS PROPERTIES DATABASE (MMPDb)**

NEW MATERIAL SELECTION REQUIREMENTS (MSR)



- Requirements driven by consequences of failure
- FTRP establishes procedures to verify that fracture performance is adequate for intended application
- Fracture-Informed design

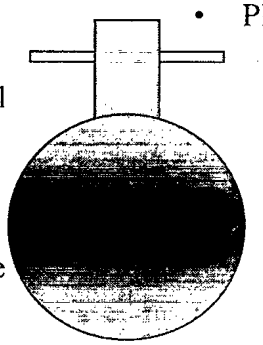
BACKGROUND

- **MOTIVATION: To prevent catastrophic failures by avoiding materials with a propensity for brittle fracture during design phase, thus focusing the material selection for critical applications on fracture-resistant materials (materials that exhibit significant plasticity in the presence of flaws)**

MATERIAL SELECTION
TRADITIONAL NAVY APPROACH

Non-nuclear, submarine applications

- NON-PRESSURE HULL BOUNDARY
  - Emphasis on mechanical and physical properties
    - Strength
    - Ductility
    - Corrosion resistance
    - Density
  - Fracture behavior not explicitly considered



- PRESSURE HULL BOUNDARY
  - Strength an Important Factor
  - BUT
  - Emphasis on fracture behavior of welds
  - AND
  - Weld system development to prevent cracking

TRADITIONAL APPROACH TO MATERIAL SCREENING

- Traditional Navy approach differentiated between pressure and non-pressure hull boundary parts
- Non-pressure hull boundary parts have been selected based on strength, ductility and corrosion resistance only
- Pressure hull boundary parts must be made of materials exhibiting significant plasticity in the presence of flaws under high strain rates
- Selections are based on explosion bulge & crack starter tests, used to qualify pressure hull materials. Successful completion of these tests qualifies material and fracture is not a concern. No additional NDE is required for workmanship level flaws. Fracture mechanics based procedures are not incorporated in design process

FRACTURE MECHANICS APPROACH TO MATERIAL SCREENING

- FTRP departs from traditional methods. Parts are differentiated as far what the impact on the consequences of failure. Can Navy live with them?
- Parts can be either critical or non-critical.
- For non-critical parts no additional review requirements are imposed beyond design specifications
- FTRP is broken down into four (4) Parts, I,II,III, & IV. Part I is invoked. It may or may not trigger the other parts.

  Part II provides screening criteria and quantifies whether material provides significant plasticity. At this point either the traditional Navy approach or the fracture mechanics based approach can be used.

FRACTURE MECHANICS BASIS FOR MATERIAL SCREENING

- **Fundamental basis of fracture mechanics:**
  - **All Engineering Materials contain defects**

  Defects vary in size from nano-scale to macro-scale. Macro-defects are within the capability of NDE methods.

  Flaws or cracks act like stress raisers, thus giving rise to plastic deformation locally

  Severity of stresses & strains at the crack tip is characterized by Stress Intensity Factor (SIF) K in linear fracture mechanics (LEFM) and by J in Elastic-plastic (EPFM) fracture mechanics

FRACTURE MECHANICS BASIS FOR MATERIAL SCREENING (Cont'd)

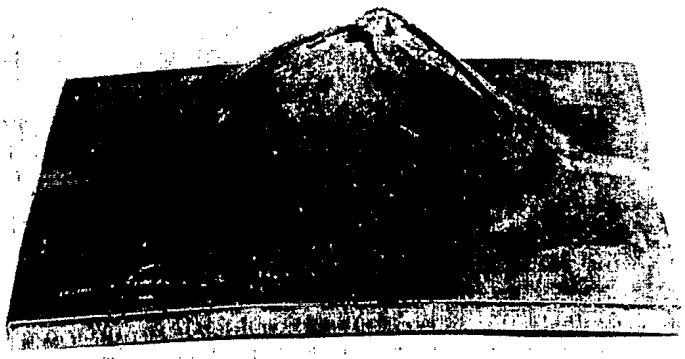
- **Material's Resistance to Growth of pre-existing crack is referred to as FRACTURE TOUGHNESS. It is a material property under plain strain conditions (K_{ic}) for LEFM and for EPFM (J_{ic})**
- **Material's increasing Resistance to additional Growth is referred to as TEARING MODULUS (T). Not a material property**

What Combination of Strength and Fracture Toughness is adequate for a material to develop significant plasticity under high strain rates in the presence of flaws?

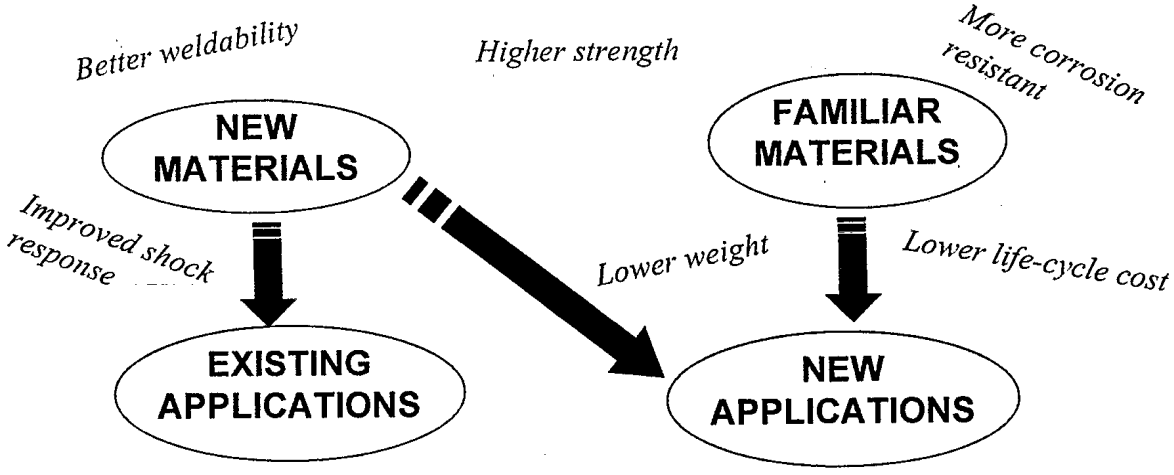
- **NRL (Pellini) developed RAD shown next. This method correlated Dynamic Tear Test (DT) with Yield Strength**
- **Traditional Strength of Materials emphasize plastic deformation, buckling failure modes, excessive deflections but do not address flaws**
- **FTRP addresses question by employing Failure Assessment Diagram (FAD), the locus of fracture & overload competing failure modes**

EXPLOSION BULGE TEST

- Bi-axial tension opens existing flaws
- Explosive loading - high strain rate
- Large plastic deformation
- Thick section - high constraint

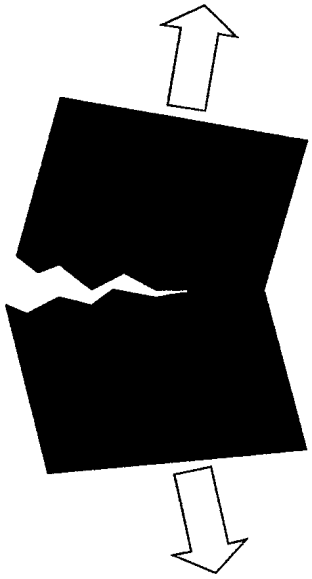


NEW PERFORMANCE REQUIREMENTS DRIVE MATERIAL SELECTION



NO MATERIAL IS FRACTURE-PROOF

- Possibility of fracture determined by:
  - Applied Load
  - Flaw Size
  - Material Properties



"GOOD" MATERIAL CHARACTERISTICS

- What do we mean by a "GOOD" material, from a fracture point of view?
  - High Fracture Toughness, K_{mat}
  - High Tearing Resistance, T
  - High Toughness to Yield Ratio, K_{mat}/σ_{ys}
  - Good resistance to EAC

Even "GOOD" materials can fail by fracture if flaws are large enough, stresses high enough and design promotes it.

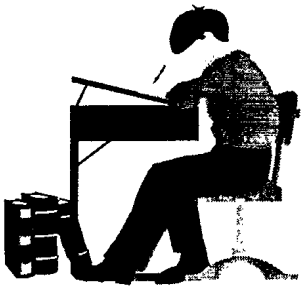
FTRP MATERIAL SCREENING CRITERIA

- TRADITIONAL
  - Pass structural element test such as Explosion Bulge, HTE or ETT.
  - Resistant to EAC
- *Focus is on overall structural behavior*
- *Extreme test - not applicable to some applications*
- *Does not measure a material property*

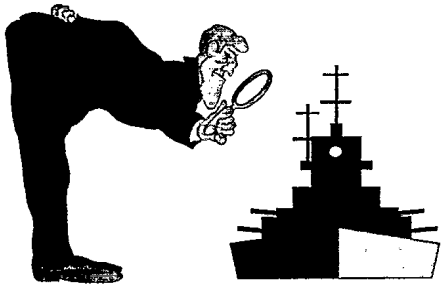
- FRACTURE MECHANICS
  - Meet minimum Flaw Tolerance
  - Meet minimum Tearing Modulus
  - Resistant to EAC
  - Confirmation with structural element test
- *Focus is on material properties that govern structural behavior*
- *Small specimen testing*
- *Evaluate influence of chemistry, product form, processing, fabrication and repair on fracture behavior*

WHAT IF MATERIAL DOES NOT PASS SCREENING?

Select Alternate Material



OR



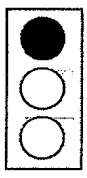
Evaluate specific part for intended application (Parts III & IV)

PART III : FLAW ASSESSMENT

- Determine if largest crack that could be missed would be critical under the most severe loading conditions at start of life. This requires knowledge of:
  - Materials, design and fabrication
  - NDE detection limits
  - Stresses in part
  - Material properties
  - Factors of Safety

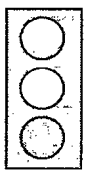
PART IV : SUB-CRITICAL CRACK GROWTH

- Sub-critical crack growth mechanisms
  - *Fatigue*
  - *Stress Corrosion Cracking*
  - *Sustained Load Cracking*
- Determine if initial flaws could grow to critical size before end-of-life.



YES

Initial NDE + Periodic inspection and/or part replacement



NO

Initial NDE

MATERIAL SELECTION REQUIREMENTS

- **NAVY METALLIC MATERIALS PROPERTIES DATABASE**
- **Proposed electronic database tool to assist designers in selection of materials for critical applications**
- **Provides material properties and characteristics to enable activity use of the MSR and FTRP**
- **MARINE GRADE HIGH STRENGTH FASTENERS HANDBOOK**
- **Provides fastener alloy data, input to database**

NAVY MATERIALS PROPERTY DATABASE

E. J. Czyryca
Naval Surface Warfare Center
Carderock Division / Metals Department

301 227 5073
czyrycaEJ@nswccd.navy.mil

NAVY MATERIALS PROPERTY DATABASE

Objective: Provide all material system information in an accessible source to support design agent material selection and design of ship and submarine structures and machinery components. For critical applications, facilitate

NAVSEA Material Selection Requirements (MSR)

NAVSEA Fracture Toughness Review Process (FTRP)

[electronic database + expert system]

Navy Design Agent Metallic Material Selection

- *Material Selection Requirements (MSR)*

  ⇒**Provides guidance and direction for the design agent to select materials for use in critical, non-nuclear applications**

  ⇒**Requires design agent to document Material Selection Information for critical applications**

Navy Design Agent Metallic Material Selection

- *Fracture Toughness Review Process (FTRP)*

  ⇒Provides detailed ***method*** for assessing fracture safety for critical, non-nuclear components

  ⇒Defines material properties needed to demonstrate adequate fracture resistance; e.g. K_{Ic}, J_{Ic}, K_{ID}, J_{ID}, K_{Iscc}, σ / ε curves, fatigue data (S/N, da/dN - ΔK)

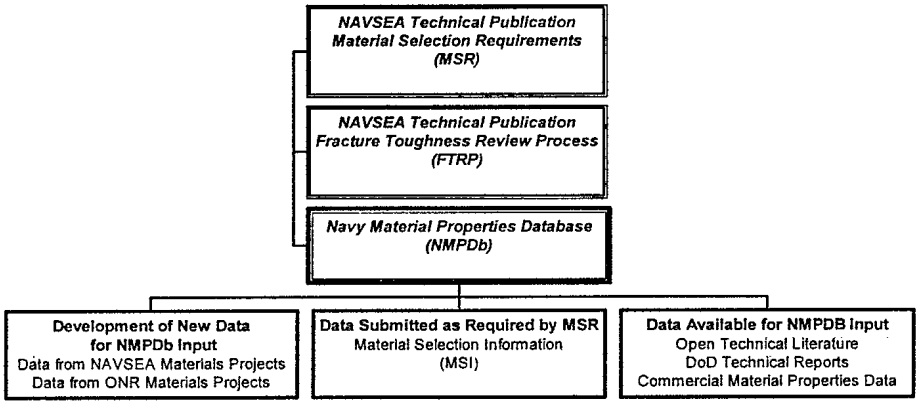
Navy Design Agent Metallic Material Selection

Navy Materials Properties Database

⇒Proposed electronic database tool to assist designers in selection of materials for critical applications

⇒Provides material properties and characteristics to enable design activity use of the MSR and FTRP

NAVY MATERIALS PROPERTY DATABASE



NAVY MATERIALS PROPERTY DATABASE

USAF, FAA, and NASA design activity resources for material properties for design and analysis:

- **Metallic Materials and Elements for Aerospace Vehicle Structures, MIL-HBK-5G / 2 vols.**
- **Aerospace Structural Metals Handbook / 5 vols**
- **Derivation of Crack Growth Properties of Materials for NASA/FLAGRO 2.0 / 3 vols**
- **Damage Tolerant Design Handbook / 4 vols**
- **Structural Alloys Handbook / 3 vols**

These resources are being converted to electronic format

MATERIAL CHARACTERISTICS TO BE ADDRESSED
Navy metallic systems vs Aerospace alloys

- ✓ EFFECT OF MARINE ENVIRONMENTS / EFFECT OF APPLIED CATHODIC POTENTIAL
- ✓ MAGNETIC PROPERTIES
- ✓ LOW-CYCLE FATIGUE / CORROSION FATIGUE
- ✓ WELDABILITY AND THE PROPERTIES OF WELDMENTS (HAZ & WELD METAL)
- ✓ BALLISTIC LIMITS FOR PROTECTION APPLICATIONS
- ✓ FRACTURE TOUGHNESS OF THICK SECTIONS AND WELDS AT LOW TEMPERATURE
- ✓ UNDEX OR AIR BLAST LOADING RATES

NAVY MATERIALS PROPERTY DATABASE

- **Phase I - Database Project Definition**
  - Establish NMPDb Working Group / Database scope & requirements
  - Establish data format & data presentation / data evaluation criteria
- **Phase II - Database Interim Format**
  - Software development / data retrieval / prioritize material sets & properties for interim format
  - Interim format / review & comment
- **Phase III - Database Expansion**
  - Software refined / expert system functions implemented
  - Expand database material sets & properties
  - Customer trials / review & tailor
- **Phase IV - Database Implementation & Maintenance**
  - Stand-up database / formalize database & software maintenance

NAVY MATERIALS PROPERTIES DATABASE WORKING GROUP ISSUES

- DATABASE REQUIREMENTS
- DATA REQUIREMENTS
- DATA RETREIVAL / COLLECTION
- DATA QUALITY EVALUATION PROCESS
- DATA ENTRY / VALIDATION & APPROVAL PROCESS
- DATABASE VIRTUAL LIBRARY
- HARDWARE / SOFTWARE REQUIREMENTS

NAVY MATERIALS PROPERTY DATABASE

AMPTIAC

Advanced **M**aterials and **P**rocesses **T**echnology
Information **A**nalysis **C**enter, Rome NY

- Administered by Defense Technical Information Center, operated by IIT Research Institute
- Consolidates previous materials IAC's
- Maintains defense materials library holdings
- Material database development / maintenance core mission
- Metals expertise (data evaluation) / DBMS software expertise

SUGGESTED INITIAL SET OF ALLOYS for NMPDb

Structural Steels	HY-80/100 Steel HSLA-80/100 Steel
Machinery Steels	Ni-Cr-Mo Steels Cr-Mo Steels
Stainless Steels	17-4 PH Steel XM-13 Steel Ferralium A286
Nickel Alloys	Alloy 625 Inconel 718 Monel K-500 Monel 400 H-Monel (cast)

SUGGESTED INITIAL SET OF ALLOYS for NMPDb

Copper Alloys	Ni-Al Bronze Hiduron (Cu-Ni) Copper-Be
Titanium Alloys	CP Titanium Gr. 2 CP Titanium Gr. 3 CP Titanium Gr. 3 Ti-6Al-4V ELI/VLI grades
Aluminum Alloys	5086 Al-Mg 5456 Al-Mg 6061-T6
Superalloys	MP159 / MP35N Haynes Alloy 25

LIST OF MATERIAL CHARACTERISTICS TO BE INCLUDED IN NMPDb

- Material system commentary
- Base Metal Mechanical Properties
- Base Metal Physical properties
- Weldment Mechanical Properties (Weld metal & HAZ)
- Weld metal physical properties
- Material system welding characteristics
- Material system fabrication characteristics

SUGGESTED LIST OF CHARACTERISTICS TO BE INCLUDED IN NAVY METALLIC MATERIALS PROPERTY DATABASE

I. MATERIAL SYSTEM COMMENTARY
- A. Description of alloy system
- B. Product forms [plate / thickness range, castings, forging]
- C. Manufacturing considerations [machining, surfacing, cutting]
- D. Fabrication considerations [welding, forming, fastening]
- E. Heat treatment considerations
- F. Environmental considerations
- G. Cost factors [relative]
- H. Availability [of all product forms]
- I. Specifications
- J. Service applications [prior experience in naval systems]

II. BASE METAL MECHANICAL PROPERTIES [for each product form in all possible options for heat treatment, stress relief, etc. and for full thickness range]
- A. Tensile properties
  1. tensile properties for longitudinal, transverse, and through-thickness
  2. precision stress-strain curves to large plastic strain
  3. true stress-true strain curves
  4. strain hardening characteristics
  5. cold-forming effects (pre-strain, Baushchinger effect)
  6. high strain-rate tensile properties
  7. effects of elevated temperature
  8. effects of cryogenic temperature

- B. Compression properties
  1. compression properties for longitudinal, transverse, and through-thickness
  2. precision stress-strain curves to large plastic strain
  3. true stress-true strain curves
  4. strain hardening characteristics
  5. cold-forming effects (pre-strain, Baushchinger effect)
  6. high strain-rate compression properties
  7. effects of elevated temperature
  8. effects of cryogenic temperature

C. Elastic constants
   1. elastic modulus (tension / compression)
   2. shear modulus
   3. Poisson's ratio

D. Hardness

E. Shear strength
   1. direct shear
   2. torsional shear

F. Fracture toughness properties
   1. K_{Ic} / J_{Ic} versus temperature
   2. K_{Id} / J_{Id} versus temperature
   3. Charpy V-notch impact toughness versus temperature
   4. dynamic tear impact toughness versus temperature
   5. nil-ductility transition temperature [ferrous products]
   6. crack-arrest toughness

G. Fatigue properties
   1. cyclic stress-strain curves
   2. low-cycle fatigue (strain-range vs. cycles to crack initiation)
   3. high-cycle fatigue (S/N curves)
   4. fatigue crack growth rate curves

H. Marine corrosion properties
   1. general corrosion
   2. crevice corrosion
   3. galvanic corrosion
   4. high-velocity corrosion
   5. corrosion Fatigue
      a) low-cycle fatigue (strain-range vs. cycles to crack initiation)
      b) high-cycle fatigue (S/N curves)
      c) fatigue crack growth rate curves
      d) effects of cathodic/anodic potentials
   6. stress corrosion
      a) uncracked, direct exposure
      b) stress corrosion cracking resistance (K_{Iscc})
      c) effects of cathodic/anodic potentials

I. Ballistic limits

J. Frictional properties
   1. coefficient of friction vs. other metals
   2. lubricants
   3. galling & seizing

III. BASE METAL PHYSICAL PROPERTIES
A. Density

B. Thermal properties
   1. melting point [range]
   2. specific heat
   3. thermal conductivity
   4. thermal expansion

C. Magnetic properties
   1. magnetic permeability

D. Electrical properties
   1. electrical resistivity

E. Microstructural characteristics
   1. phase diagram
   2. typical microstructures
   3. critical transformation temperatures
   4. TTT & CCT diagrams

IV. WELDMENT MECHANICAL PROPERTIES (Weld metal & HAZ) [for each product form, all welding processes for full thickness range with applicable welding consumables and welding positions]
A. Tensile properties
   1. tensile properties for all weld metal and transverse (across the weld)
   2. precision stress-strain curves to large plastic strain (all weld metal)
   3. weld metal true stress-true strain curves
   4. weld metal strain hardening characteristics
   5. weld metal high strain-rate tensile properties
   6. effects of elevated temperature
   7. effects of cryogenic temperature

B. Compression properties
   1. compression properties for all weld metal and transverse (across the weld)
   2. true stress-true strain curves
   3. strain hardening characteristics

C. Elastic constants [weld metal]
   1. elastic modulus (tension / compression)
   2. shear modulus
   3. Poisson's ratio

D. Hardness
   1. profile across weld & HAZ
   2. through multi-pass weld

E. Shear strength
   1. weld metal direct shear
   2. weld metal torsional shear
   3. longitudinal shear of fillet welds
   4. transverse shear of fillet welds

F. Charpy V-notch impact toughness versus temperature
   1. all weld metal with V-notch in welding direction
   2. HAZ with V-notch 1 mm from fusion line

G. Fracture toughness properties
   1. K_{Ic} / J_{Ic} of weld metal versus temperature
   2. K_{Id} / J_{Id} of weld metal versus temperature
   3. dynamic tear impact toughness of weld metal versus temperature
   4. K_{Ic} / J_{Ic} of HAZ versus temperature
   5. K_{Id} / J_{Id} of HAZ versus temperature
   6. dynamic tear impact toughness of HAZ versus temperature
   7. nil-ductility transition temperature [ferrous weld metals]
   8. crack-arrest toughness of weld metal

H. Explosion tests
   1. explosion bulge test series
   2. crack-starter explosion bulge test series
   3. explosion tear (hull toughness element) tests

I. Fatigue properties
   1. cyclic stress-strain curves for weld metal
   2. low-cycle fatigue of weld metal (strain-range vs. cycles to crack initiation)
   3. low-cycle fatigue of weldment (strain-range vs. cycles to crack initiation)
   4. high-cycle fatigue of weldments (S/N curves)
   5. fatigue crack growth rate curves for weld metal & HAZ

J. Marine corrosion properties
   1. welded panel general corrosion (preferential weld/HAZ attack)
   2. crevice corrosion (as above)
   3. high-velocity corrosion (as above)
   4. corrosion fatigue of weldments
      a) low-cycle fatigue of weldment (strain-range vs. cycles to crack initiation)
      b) high-cycle fatigue of weldment (S/N curves)
      c) fatigue crack growth rate curves
      d) effects of cathodic/anodic potentials
   5. stress corrosion
      a) uncracked, direct exposure
      b) stress corrosion cracking resistance (K_{Iscc})
      c) effects of cathodic/anodic potentials

K. Ballistic limits

L. Dissimilar metal weldment properties
   1. full strength butt joints
   2. attachments / stud welding
   3. weld cladding / surfacing

V. WELD METAL PHYSICAL PROPERTIES
   A. Density
   B. Thermal properties
      1. melting point [range]
      2. specific heat
      3. thermal conductivity
      4. thermal expansion
   C. Magnetic properties
      1. magnetic permeability
   D. Electrical properties
      1. electrical resistivity

E. Microstructural characteristics
   1. phase diagram
   2. typical microstructures
   3. critical transformation temperatures
   4. TTT & CCT diagrams

VI. MATERIAL SYSTEM WELDING CHARACTERISTICS

A. Weldability (sensitivity to cracking) properties
   1. root bend, face bend, & side bend tests
   2. restrained-root cracking / keyhole restraint tests
   3. cruciform tests
   4. implant tests
   5. circular patch / circular fillet tests
   6. trough tests
   7. controlled thermal severity tests
   8. varestraint / transvarestraint hot-cracking tests
   9. long-plate restrained weld tests

B. Welding process operational envelope limits
   1. At lowest preheat & interpass temperature limits [highest weld metal C.R.]
   2. At highest preheat & interpass temperature limits [Lowest weld metal C.R.]

VII. MATERIAL SYSTEM FABRICATION CHARACTERISTICS

A. Manufacturing data
   1. machining information
   2. punching, shearing, sawing, cutting information
   3. cold forming procedures / limits
   4. fasteners / fastening procedures

B. Welding procedures
   1. welding process procedures and qualification
   2. repair welding
   3. NDE procedures