FINESSE

A STUDY ON THE ISSUES, PHENOMENA AND EXPERIMENTS FOR FUSION NUCLEAR TECHNOLOGY

DISCUSSIONS WITH DOE
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FINESSE

A Study on the Issues, Phenomena and Experiments for Fusion Nuclear Technology

Objective

- Investigate the technical and programmatic issues in the development of fusion nuclear technology.
- Provide input on the key elements of the most logically consistent path for fusion nuclear technology that maximizes technical benefits and minimizes cost.

Nuclear Technology

- Fuel Production, Energy Extraction and Use
  - Plasma Interactive Components (First Wall, Impurity Control and Exhaust, Etc.)
  - Blanket
  - Shield
  - Tritium Systems

FINESSE: ORGANIZATION

- Two-Year Study (Started in November, 1983)

- Major Participation by Key U.S. Organizations

  - UCLA, ANL, EG&G, HEDL, MDAC, TRW

  - LLNL, PPPL

  - Coordination with Other DOE and EPRI Programs

- Broad Participation by Fusion Community: Advisory Committee, Workshops

- Significant International Participation

  - Germany (KfK), Japan (JAERI, Universities), Canada (CFFTP)

  - Importance:
    * All World Programs Face the Same Issues
    * International Cooperation on Nuclear Technology: Viable, Economical

  - Observation:
    FINESSE Experience with International Participation has Proved Extremely Successful Scientifically, Socially, and Politically

FINESSE: SCOPE

- Understand the Basic Scientific Phenomena Governing the Behavior and Performance of Nuclear Components in the Fusion Environment

- Identify and Characterize those Fusion Nuclear Technology Issues for which New Knowledge is Essential through:

  - Theory
  - Models
  - Experiments

- Develop the Scientific Basis for the Technical Discipline of Fusion Engineering Experiments

  - Engineering Scaling Relationships
  - Quantifying Experiment/Test Requirements

- Develop Innovative Ideas and Technical Criteria for High-Payoff, Low-Cost Fusion Engineering Experiments

  - Type of Experiments:
    1 Basic
    2 Single Phenomenon
    3 Multiple Phenomena/Interactive
    4 Integral

  - Type of Facilities:
    1 Small-Scale Non-Nuclear Test Stands
    2 Accelerator-Based Neutron Sources
    3 Fission Reactors
    4 Multiple Environment Facilities
    5 Fusion Facilities

FINESSE: PRINCIPAL TECHNICAL TASKS

I. IDENTIFICATION OF ISSUES AND REQUIRED EXPERIMENTS

II. QUANTIFICATION OF TEST REQUIREMENTS

- UNDERSTANDING AND ANALYSIS OF SINGLE AND MULTIPLE INTERACTIVE PHENOMENA
- REQUIREMENTS ON TEST CONDITIONS (E.G., POWER DENSITY, FLUENCE, SIZE, T, B)
- ISSUES OF ENGINEERING SCALING
- NEED FOR NEUTRONS AND INTEGRATED TESTING
- FIGURES OF MERIT FOR MAJOR PARAMETERS OF EXPERIMENTAL FACILITIES

III. EVALUATION OF EXPERIENCE FROM OTHER TECHNOLOGIES

A. FISSION
B. AEROSPACE

IV. SURVEY AND EVALUATION OF EXPERIMENTAL FACILITIES

A. NON-FUSION FACILITIES
B. FUSION DEVICES

V. COMPARATIVE EVALUATION OF TEST FACILITIES, SCENARIOS

VI. RECOMMENDATIONS ON FUSION NUCLEAR TECHNOLOGY DEVELOPMENT

CRITICAL FUSION NUCLEAR TECHNOLOGY ISSUES

1. DT Fuel Cycle Self Sufficiency

   - Achievable Tritium Breeding

     e.g., Effects of Blanket Material Choices and Internal Details

     Extent of Plasma Coverage (Choice of RF vs. Neutral beams, Limiter vs. Divertor)

     Uncertainties in Neutronics Methods and Data

   - Required Tritium Breeding

     e.g., Dependence on Plasma Recycling (Limiter vs. Divertor, Pumping Efficiency)

     Tritium Inventory in Blanket

     Tritium Extraction and Processing Systems Efficiencies and Inventories

2. Thermomechanical Performance of Components under Normal and Off-Normal Operation

   - Liquid Metal MHD Effects: Relationship of Fluid Flow, Heat Transfer, Corrosion, and Stresses with Full Geometric Complexity

   - Interaction of Primary and Secondary Stresses and Deformation

   - Effect of Swelling and Creep on Stress Concentrations

   - Consequences of Plasma Disruptions

   - Sources and Consequences of Hot Spots

CRITICAL FUSION NUCLEAR TECHNOLOGY ISSUES
(CONT.)

3. Materials Compatibility

- Influence on Failure Modes
  e.g., Liquid Metal Embrittlement and Stress Corrosion Cracking

- Effect on Design Limits
  e.g., Liquid Metal Corrosion Temperature Limits
  LiOT and Lithium Burnup Effects

- Impact on Safety and Reliability
  e.g., Transport of Radioactive Isotopes
  Oxidation/Volatility of Vanadium
  Lithium Chemical Reactivity
  Blocking of Coolant or Purge Streams

4. Identification and Characterization of Failure Modes and Rates

- Crack Growth and Brittle Fracture with Irradiation

- Vulnerability at Welds and Discontinuities

- Discovery of Unforeseen Failure Modes

CRITICAL FUSION NUCLEAR TECHNOLOGY ISSUES

(CONT.)

5. MAGNITUDE AND DEPENDENCE OF TRITIUM INVENTORY IN THE SOLID BREEDER VS. TEMPERATURE AND IRRADIATION UNDER ACTUAL OPERATING CONDITIONS

    - RADIATION EFFECTS ON TRITIUM DIFFUSIVITY AND SOLUBILITY

    - VARIABILITY IN TEMPERATURE DUE TO MECHANICAL AND MATERIALS INTERACTIONS (GAP CONDUCTANCE, CRACKING, SWELLING, CREEP, ETC.)

6. TRITIUM PERMEATION AND INVENTORY

    - MAGNITUDE IN IN-VESSEL COMPONENTS UNDER ACTUAL OPERATING CONDITIONS (INCLUDING EFFECTS OF PLASMA-SIDE CONDITIONS, RADIATION, ETC.)

    - FORM OF TRITIUM (T_2, T_2O) RELEASED FROM SOLID BREEDERS

    - EFFECTIVENESS OF CONTROL METHODS SUCH AS PERMEATION BARRIERS

7. IN-VESSEL COMPONENTS THERMOMECHANICAL RESPONSE AND LIFETIME

    - EROSION AND REDEPOSITION MECHANISMS AND RATES UNDER VARIOUS PLASMA EDGE CONDITIONS

    - HEAT REMOVAL TECHNIQUES

    - STRUCTURAL INTEGRITY OF COMPONENTS AND BONDS

    - LEADING EDGE DESIGN OF LIMITERS

CRITICAL FUSION NUCLEAR TECHNOLOGY ISSUES
(CONT.)

8. Radiation Shielding

- Accuracy of Prediction
- Data on Radiation Protection Requirements

9. Accuracy and Survivability of Instrumentation and Control

- Accruacy and Decalibration in the Fusion Environment
- Lifetime Limits due to Radiation Effects

TECHNICAL CONCLUSIONS WITH PROGRAMMATIC IMPLICATIONS

- The Fusion Environment Experienced by Nuclear Components is Unique and Leads to Many New Phenomena that Result from the Interaction among the Fusion Environmental Conditions, Elements within Components, and Multiple Components

  - Environmental Conditions: Plasma Particles, Neutrons, γ-rays, Magnetic Field, Heating, Tritium

  - System: Many Components with Diverse and Interrelated Functional Requirements

- These New Phenomena Result in Many Critical Issues:

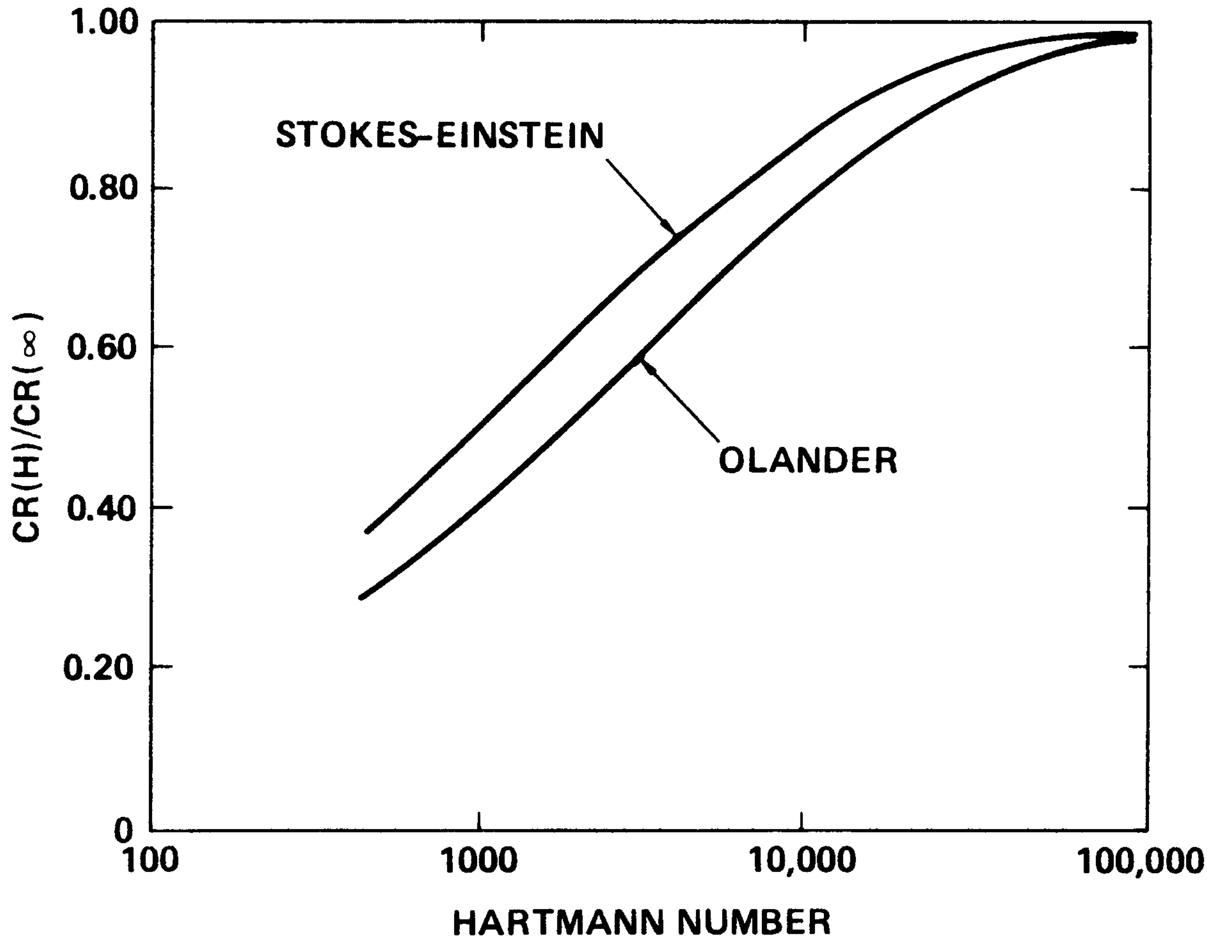
  - Feasibility Issues

  - Attractiveness Issues (Safety, Economic Potential)

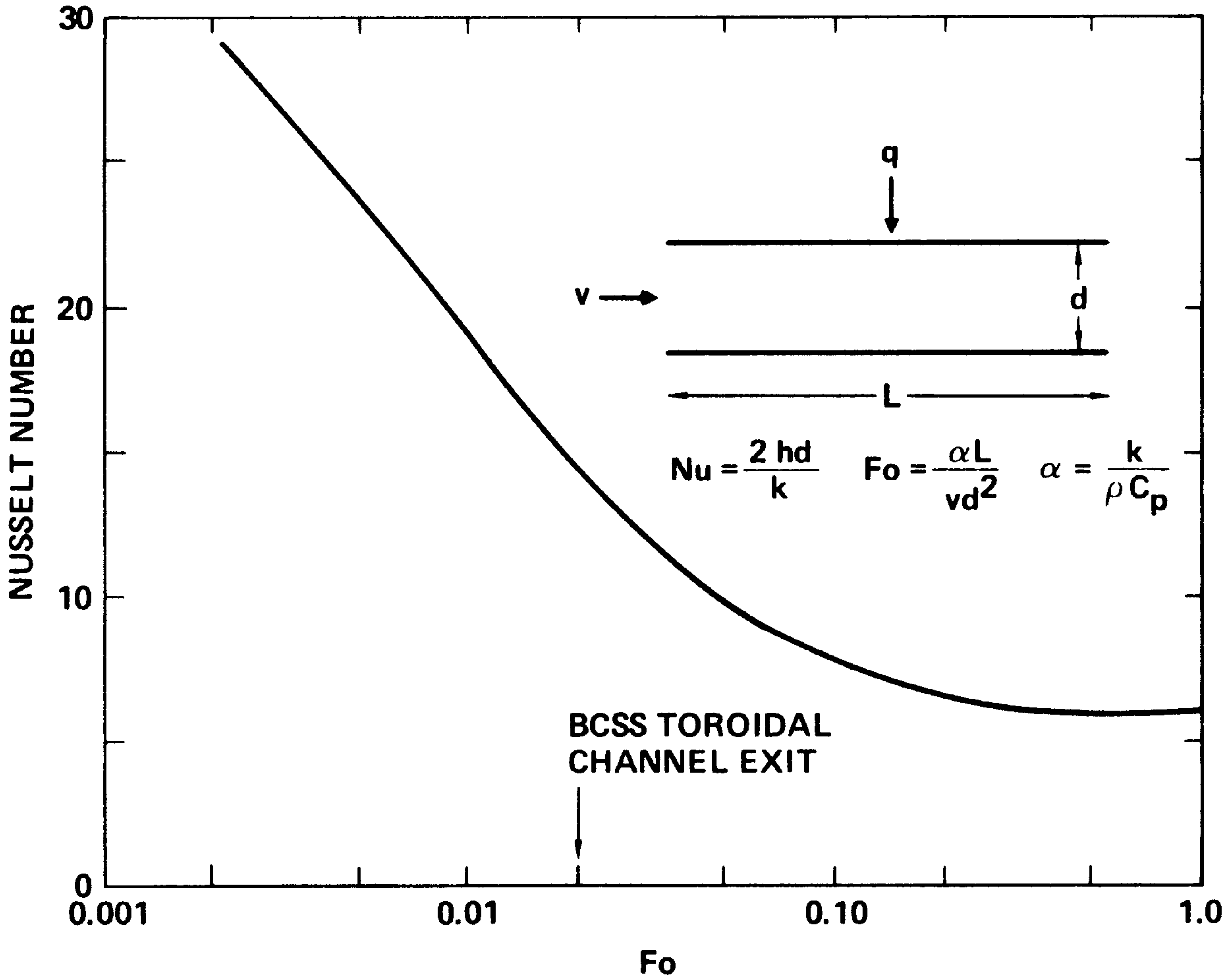
- Understanding and Characterizing these New Phenomena Requires New Knowledge that Must Be Acquired through Extensive Modelling and Carefully Planned Experiments

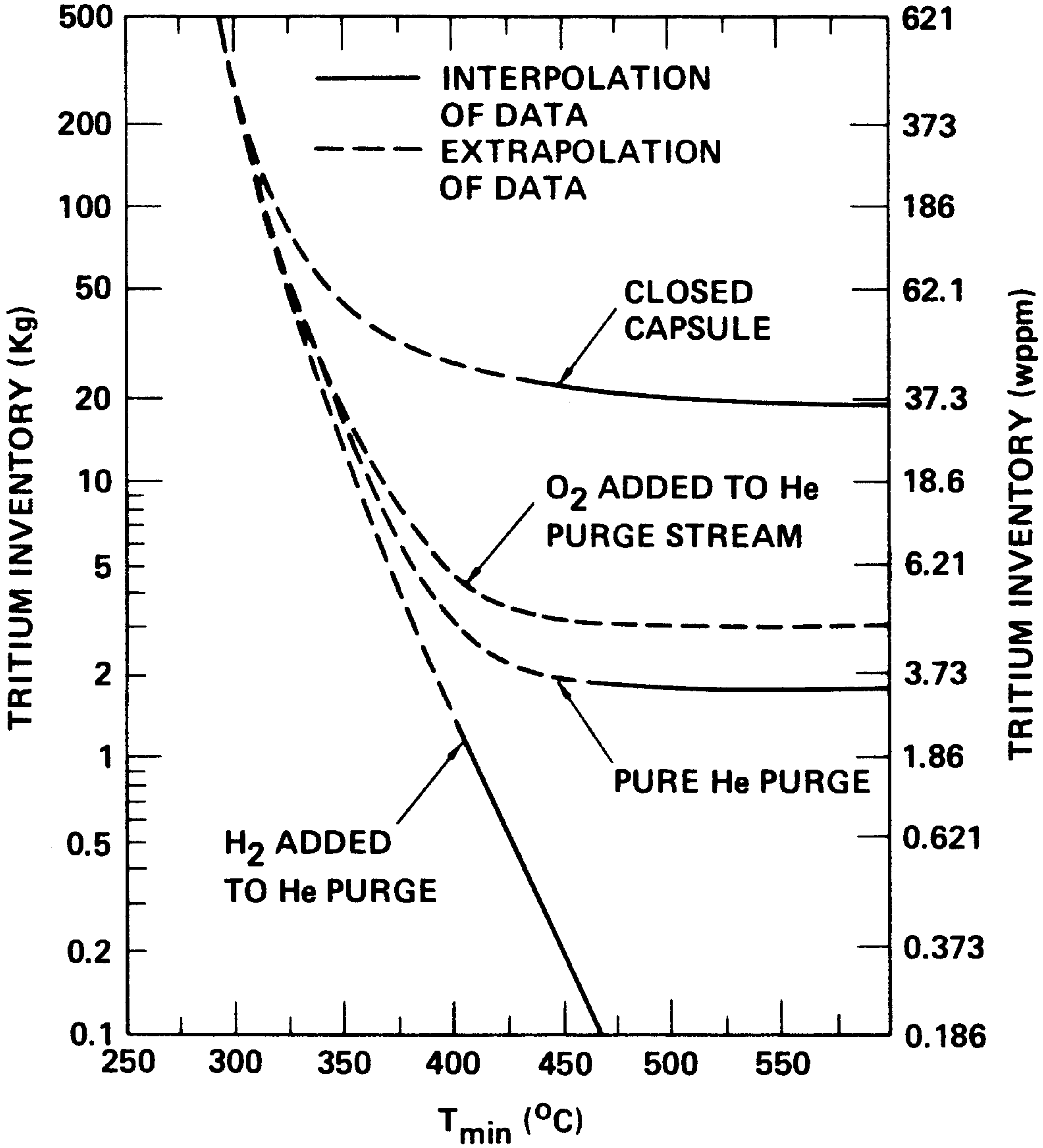
- Such Effort (Models, Experiments) in Fusion Engineering Will Combine a Number of Technical Disciplines such as Materials, Chemistry, Nuclear Physics, Thermodynamics, Fluid Mechanics, Electromagnetics, Magnetohydrodynamics, Nuclear Engineering, Mechanical Engineering and Chemical Engineering

CORROSION RATE DEPENDENCE ON MAGNETIC FIELD STRENGTH



LIQUID METAL HEAT TRANFER COEFFICIENT FOR NON-FULLY DEVELOPED FLOW DEPENDS ON TEST MODULE GEOMETRY AND FLOW CHARACTERISTICS

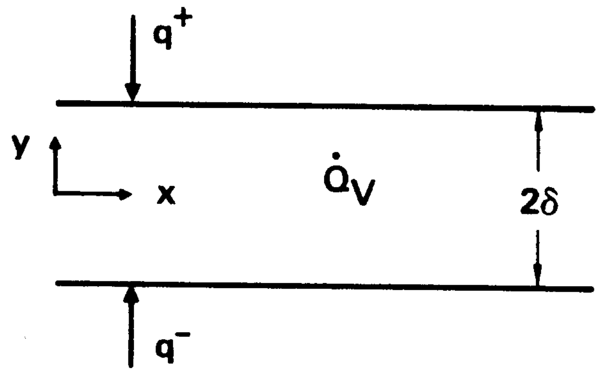




Model predictions for tritium inventory as a function of the minimum blanket temperature for the BCSS (LOBE-2B) $LiAlO_2/H_2O/Be/HT$-9 blanket. A maximum temperature of 950°C and a tritium generation rate of 866 g/day are assumed.

NUSSELT NUMBER DEPENDS ON VOLUMETRIC HEATING

Consider laminar channel flow with heat generation and surface heat flux:



Velocity profile

$$U = \frac{2n+1}{2n}\left[1 - (y/\delta)^{2n}\right] U_b = f\,(y/\delta)\,U_b$$

The Nusselt numbers are calculated as:

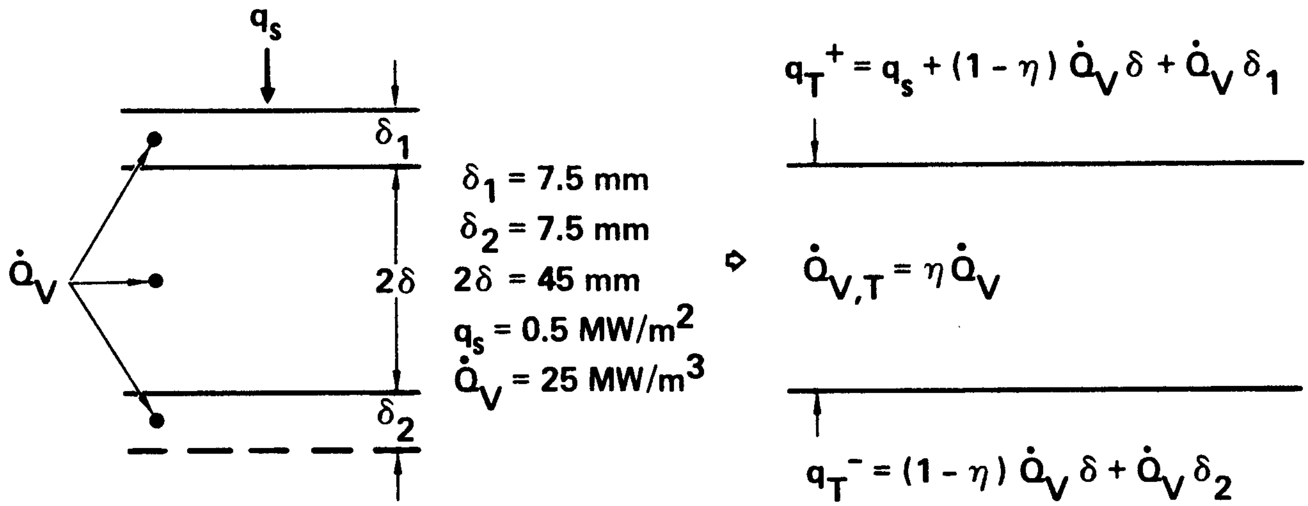
$$\frac{1}{Nu^{\pm}} = ¼ - I_1/8 - (I_1/16)(q^{\mp}/q^{\pm} - 1) + (I_2/4)(\dot{Q}_V\,\delta/q^{\pm})$$

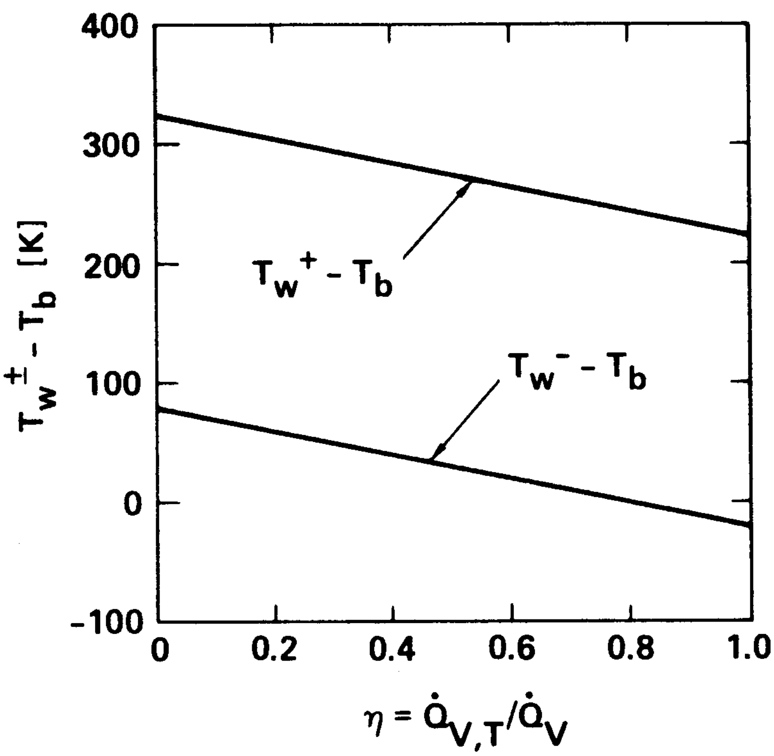
where

$$I_1 = \int_{-1}^{1} d\eta\ f(\eta) \int_{-1}^{\eta} d\eta \int_{-1}^{\eta} d\eta\ f(\eta)$$

$$I_2 = ½ \int_{-1}^{1} d\eta\ f(\eta) \int_{-1}^{\eta} d\eta \int_{-1}^{\eta} d\eta\ [f(\eta) - 1]$$

WALL TEMPERATURE AS A FUNCTION OF VOLUMETRIC HEATING IN TEST MODULE WITH TOTAL ENERGY INPUT PRESERVED





EXAMPLES OF NEW PHENOMENA/INTERACTIVE EFFECTS
LIQUID METAL BLANKETS

CORROSION

1. CLASSICAL: DEPENDENCE ON TEMPERATURE AND VELOCITY

2. FUSION ENVIRONMENT
   - NON-FULLY DEVELOPED FLOW IN THE PRESENCE OF MAGNETIC FIELD, BULK HEATING, AND RADIATION EFFECTS
   - NO ADEQUATE KNOWLEDGE TO PREDICT
     - UNCERTAINTY: MAY BE FACTOR OF 5 IN CORROSION RATE
     - IMPLICATION: MAY RULE OUT LIQUID METALS WITH CONVENTIONAL STRUCTURAL MATERIALS
   - RESEARCH IN FUSION ENGINEERING SCIENCES WITH BROAD APPLICATIONS

MHD EFFECTS

1. CLASSICAL: PRESSURE DROP FUNCTION OF VELOCITY AND MAGNETIC FIELD IN SIMPLE GEOMETRY AND LOW FIELD

2. FUSION ENVIRONMENT
   - COMPLEX GEOMETRY: VELOCITY PROFILES UNKNOWN
   - NON-FULLY DEVELOPED FLOW: VARIATION IN HEAT TRANSFER COEFFICIENT
   - SURFACE AND BULK HEATING: LARGE VARIATIONS IN TEMPERATURE PROFILES
   - HIGH MAGNETIC FIELD WITH TWO OR MORE COMPONENTS: RELIABLE CORRELATIONS NOT AVAILABLE
   - UNCERTAINTY: VERY LARGE IN MHD PRESSURE DROP AND HEAT TRANSFER
   - IMPLICATION: ARE LIQUID METAL BLANKETS FEASIBLE?
   - RESEARCH IN FUSION ENGINEERING SCIENCES WITH BROAD APPLICATIONS

TECHNICAL CONCLUSIONS WITH PROGRAMMATIC IMPLICATIONS

- NEUTRONS ARE NECESSARY FOR MANY OF THE INTERACTIVE EFFECT EXPERIMENTS. SOME OF THESE EXPERIMENTS NEED TO BE OF RELATIVELY LARGE VOLUME

- ACCELERATOR-BASED NEUTRON SOURCES:

  - USEFUL FOR CAPSULE HIGH FLUENCE TESTS AND SPECIAL PURPOSE NEUTRONICS/SHIELDING EXPERIMENTS

  - NOT USEFUL FOR MULTIPLE EFFECT EXPERIMENTS

- FISSION REACTORS:

  - USEFUL FOR SOME UNIT CELL/SUBMODULE EXPERIMENTS

  - SUITABLE FOR SOLID BREEDERS; NOT SUITABLE FOR LIQUID METALS

  - BUT, CANNOT SUBSTITUTE FOR FUSION TESTING

    * LIMITATIONS ON VOLUME (SIZE OF TEST ELEMENT, NUMBER OF TEST LOCATIONS)

    * SPECTRAL DIFFERENCES

    * LIMITATIONS ON SIMULATING FUSION ENVIRONMENT (ELECTROMAGNETIC, SURFACE HEAT FLUX, ETC.)

TECHNICAL CONCLUSION WITH PROGRAMMATIC IMPLICATIONS

(CONT.)

- MULTIPLE EFFECT AND INTEGRAL EXPERIMENTS FOR FUSION NUCLEAR TECHNOLOGY REQUIRE A FACILITY WITH NEUTRONS:

  NEUTRON POWER: ~ 10-50 MW
  TOTAL SURFACE AREA: ~ 10-25 m^2
  LIMITING SIZE OF AN EXPERIMENT: 1 x 1 x 1 m^3
  FLUENCE: 2-10 MW-y/m^2

- THE ONLY FACILITY APPEARS TO BE

  FUSION DEVICE

- COMBINING PHYSICS AND TECHNOLOGY EXPERIMENTS IN A SINGLE TOKAMAK INTRODUCES HIGH RISK AND HIGH COST

  - PHYSICS REQUIRES: LARGE DEVICE POWER, LOW FLUENCE
  - TECHNOLOGY REQUIRES: LOW DEVICE POWER, HIGH FLUENCE
  - COMBINING: LARGE POWER, HIGH FLUENCE
    * NEED FOR TRITIUM: BLANKET WITHOUT PRIOR FUSION TESTING? COST AND RISK
    * SHIELDING FOR HIGH FLUENCE IN LARGE DEVICE IS COSTLY

- A CRITICAL REQUIREMENT FOR A REALISTIC FUSION ENGINEERING RESEARCH FACILITY (FERF) IS A CONFINEMENT CONCEPT IN WHICH POWER AND POWER DENSITY ARE DECOUPLED

GENERAL FRAMEWORK FOR FUSION NUCLEAR TECHNOLOGY DEVELOPMENT

Now to Mid-1990's

- Utilize Existing Facilities (Test Stands, Point Neutron Sources, Fission Reactors)
- Build a Number of Small-Scale Experimental Facilities
- Consider Constructing a Partially Integrated Test Facility (PITF), e.g., Facility for Experiments on Liquid Metal Blanket and Transport Loop in All Relevant Environmental Conditions (Vacuum, Tritium, Magnetic Field) Except Neutrons

After Mid-1990's

- Continue Experiments in Non-Fusion Facilities
- Testing in a Fusion Facility

Implement Special Purpose Facility Dedicated to Fusion Engineering Research Experiments?

IS A FUSION ENGINEERING RESEARCH FACILITY WORTH CONSIDERING?

- There Appear to be Many Incentives to Studying the Technical and Programmatic Aspects of Such a Facility

- Justification: Technical Benefits

  1. Important to Fusion
     Experiments in FERF will Address Many of Fusion's Feasibility and Attractiveness (Safety, Economic Potential) Issues

  2. Important to Science and Technology
     Will Acquire New Knowledge, Data and Understanding of Many Phenomena that are Important to Many Disciplines of Science and Technology Outside of Fusion

- Programmatic Benefits

  - Funding for the Fusion Program has Expanded in the Past, Primarily Based on Plasma Physics Justification (Success and Importance to Fusion and Science). Engineering has been Perceived to Require Modest Advances as Needed for Plasma Confinement Experiments

  - If We Now Succeed in Pointing Out that Fusion Technology Must Proceed in Its Own Right (because of Importance to Fusion and Science/Technology), the Perception of the Importance and Needs of the Fusion Field May Improve, Thus Enhancing the Prospects for Additional Funding

PROGRAMMATIC ISSUES IN ENHANCING FUSION TECHNOLOGY EFFORT

• Small Scale Experiments in Fission Reactors and Test Stands		
• PITF		
• FERF		* Theory, Models

Cost

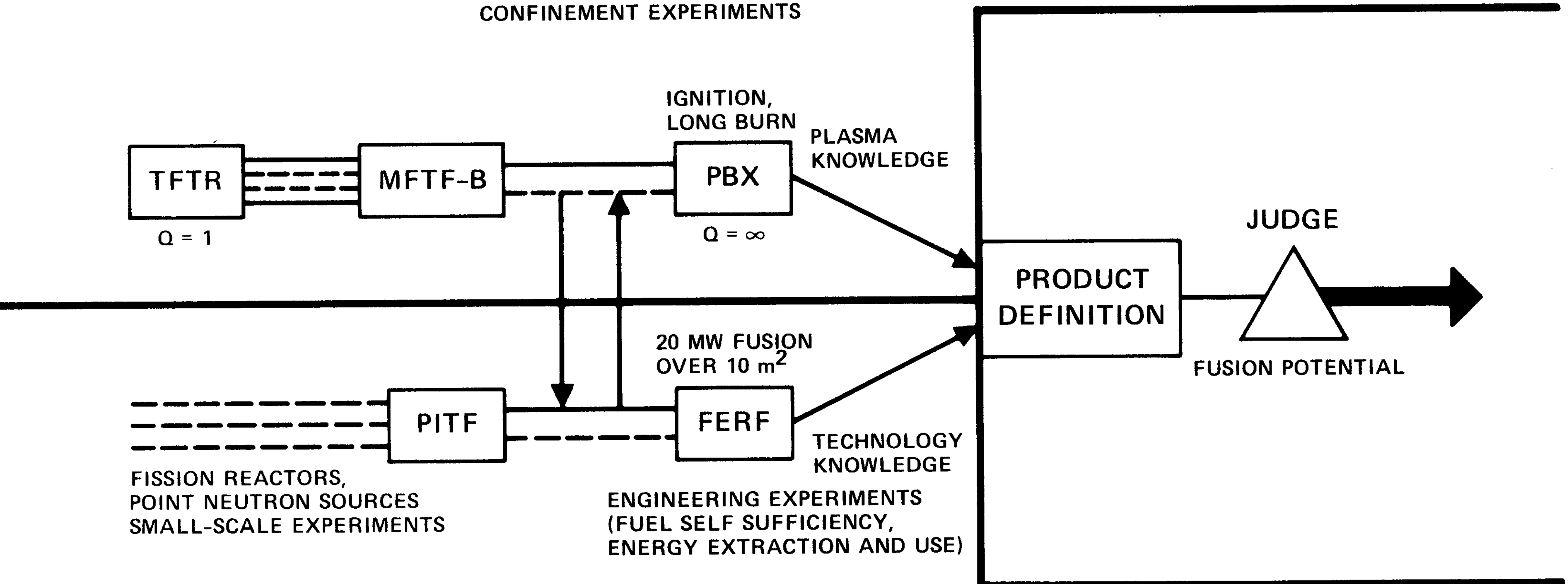
- Hopefully, Supplemental U.S. Funding May become Available for Fusion Technology in Its Own Right
- Prime Area for Strong INTERNATIONAL Cooperation
  - Many and Diverse Experiments are Needed: A Plan Among Major Countries Can be Developed
  - PITF and FERF:
    - * User-Type Facility
    - * Share Cost and Benefits without Necessity for Agreeement on Common Path

Type of Facility

- Need ~ 20 MW of Neutron Power over ~ 10 m^2 at Minimum Cost and Acceptable Risk
- Primary Purpose of Plasma is to Produce Neutrons; Should Not be Restricted to Conventional ($Q = 1$ to ∞) Physics Mode
- Tokamaks? Mirrors? Alternate Concepts?
- The **Goal** of Producing 20 MW/10 m^2 May by Itself Provide New Incentives for **Physics Discoveries**. This Goal Can Also Capture the Imagination of the Nation.

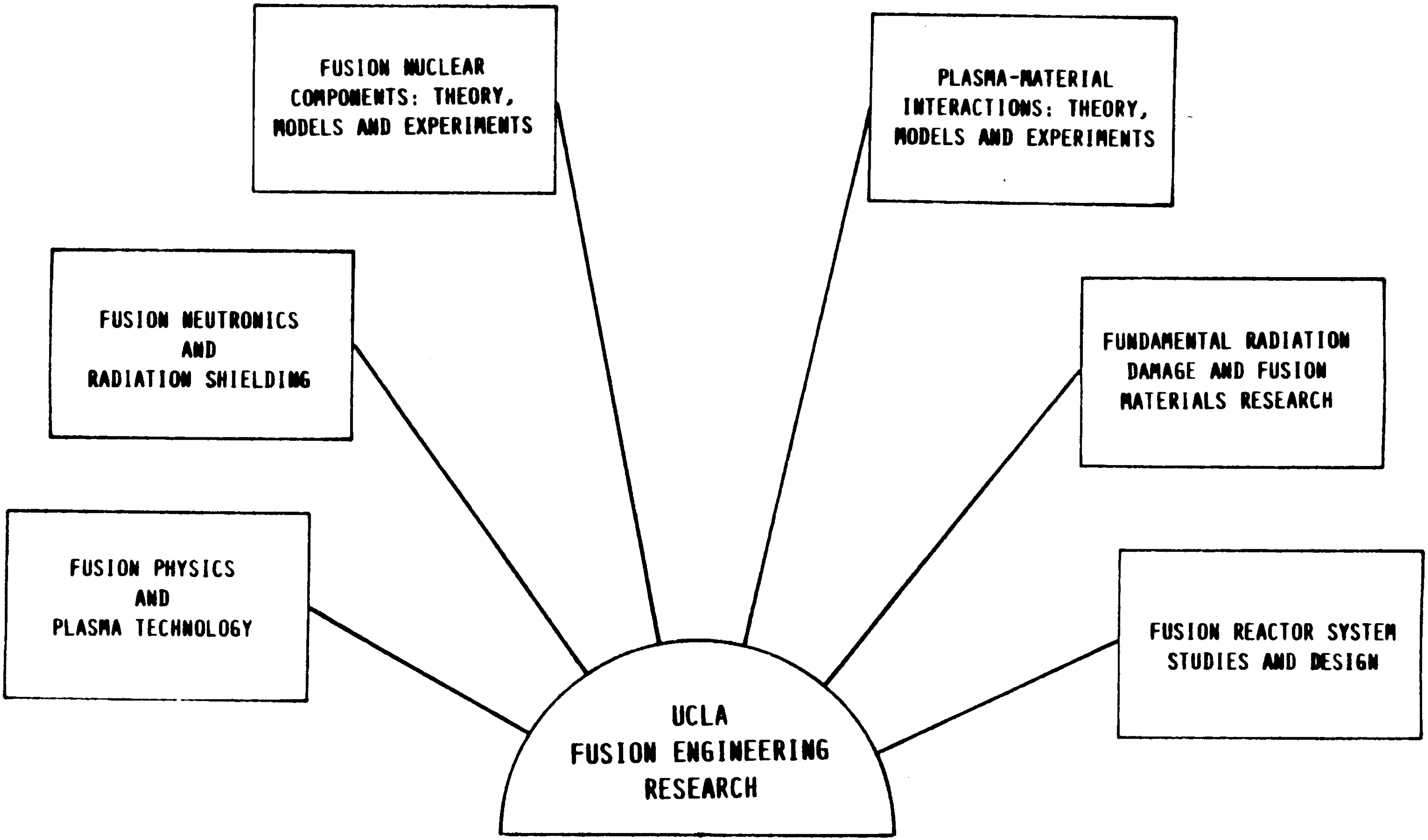
PHYSICS

- UNDERSTAND PLASMAS
- IMPROVE REACTOR CONCEPTS
  - –ENGINEERING SUPPORTS CONFINEMENT EXPERIMENTS



TECHNOLOGY

- UNDERSTAND FUSION ENGINEERING SCIENCES
- LEARN MATERIALS, ENGINEERING LIMITS IN FUSION ENVIRONMENT
- IMPROVE REACTOR CONCEPTS
  - –PLASMA PHYSICS SUPPORTS FUSION ENGINEERING EXPERIMENTS (AND PROVIDES FEEDBACK TO PRIMARY PLASMA PATH)


FUSION NUCLEAR COMPONENTS: THEORY, MODELS AND EXPERIMENTS
PLASMA-MATERIAL INTERACTIONS: THEORY, MODELS AND EXPERIMENTS
FUSION NEUTRONICS AND RADIATION SHIELDING
FUNDAMENTAL RADIATION DAMAGE AND FUSION MATERIALS RESEARCH
FUSION PHYSICS AND PLASMA TECHNOLOGY
FUSION REACTOR SYSTEM STUDIES AND DESIGN
UCLA FUSION ENGINEERING RESEARCH