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AN OVERVIEW OF THE FAST REACTORS FUELS PROGRAM

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Each nation involved in LMFBR development has its unique energy strategies which consider energy growth projections, uranium resources, capital costs, and plant operational requirements. Common to all of these strategies is a history of fast reactor experience which dates back to the days of the Manhatten Project and includes the CLEMENTINE Reactor, which generated a few watts, LAMPRE, EBR-I, EBR-II, FERMI, SEFOR, FFTF, BR-1, -2, -5, -10, BOR-60, BN-350, BN-600, JOYO, RAPSODIE, Phenix, KNK-II, DFR and PFR. Fast reactors under design or construction include PEC, CRBR, SuperPhenix, SNR-300, MONJU and Madras (India). The parallel fuels and materials evolution has fully supported this reactor development. It has involved cermets, molten plutonium alloy, plutonium oxide, uranium metal or alloy, uranium oxide, and mixed uranium-plutonium oxides and carbides.

The most recent reactors are designed to produce about ten million times more energy than the first facility, CLEMENTINE (Figure 1). Changes in fuel design have been less dramatic (Figure 2), but significant revolutionary changes are still in progress, particularly in cladding/duct applications. It is noteworthy that much of the fuel now in operation is enriched with uranium rather than plutonium and that renewed emphasis is being placed on carbide fuel development. The use of uranium reflects a shortfall of reprocessing capacity, whereas the new work on carbide fuels is motivated by long-term needs for high breeding gain systems.

Details of fuel pin design still evolve but the smear density seems to have narrowed to 80-85% of theoretical; the pitch-to-diameter ratio (tightness of pins in an assembly) still varies from country to country, with values from 1.14 to 1.30 largely dependent upon the details of the spacer system.

The evolution of fuel design is based upon a very significant world-wide irradiation experience with both experimental oxide fuel pins and driver pins used in existing reactors. Figure 3 shows that more than 12,000 experimental oxide fuel pins have been irradiated in support of fuel designs used in reactors summarized in Figure 1. A significant number of these experimental fuel pins have received substantial postirradiation examinations. The overall total of more than 300,000 irradiated oxide pins proves that a reliable fuel exists, although dramatic improvements in fuel performance and economics are being sought in every country.

About 15 years ago the fuels development program in the United States focused on mixed uranium-plutonium oxide pellet fuel in a stainless steel cladding. The U.S. experimental program has involved the irradiation of a large number of experimental assemblies in EBR-II.(1) These tests used highly characterized pins in experiments designed for precise evaluation of pin and assembly design variables and operation characteristics. A summary of the results of this program is presented in Table I. Full confirmation of the performance capabilities of the reference design is a major goal of the Fast Flux Test Facility (FFTF) program. The FFTF provides the unique tool - in combination with EBR-II, TREAT, and other facilities - to fully characterize the performance of candidate fuel systems with extensive in-core instrumentation capabilities. It also provides the basis for longer term innovative improvements and design changes for LMFBR's.(2)

The overall U.S. fuels development program emphasizes mixed-oxide fuels, but also includes a major continuing effort on mixed-carbide fuel. Specific objectives of the latter would include a breeding ratio of at least 1.30, doubling times of 10 years or less, and peak burnup capabilities of 150 MWd/kgm.(3) Carbide as well as oxide blanket fuel concepts are also being evaluated.

Summarizing the fuels irradiation program, it has been found that reference fuels can reliably achieve burnups in excess of present goals. Breaches, when they occur, are very small and have exhibited no measurable influence on neighboring fuel pins. Dimensional changes with burnup occur in a predictable, acceptable manner. Fuel-cladding chemical interaction increases with temperature, but is reduced for fuel with the lower O/M ratio. The power level required to melt fresh fuel is acceptably high and quickly increases about 20% with irradiation. Initial problems with fretting attack between pins and spacers have been solved by controlling the bundle "tightness."

The world-wide data base for fuels performance provides a sound basis for further improvements. Representative ranges of parameters studied include fuel composition from 0 to >40% plutonium, cladding diameters from 5 to 10 mm, fuel smeared density from 74 to 90% of theoretical, and peak cladding temperatures to more than 700°C.

Turning now to materials development, a prime goal of these programs has been to increase fuel lifetimes, mostly by improving cladding and duct materials.

Reduction of cladding and duct swelling appears to be the most promising route for achieving increased lifetimes. Major factors affecting swelling (Figure 4) include cold work, chemical composition, fabrication methods, primary and secondary metallurgical phase stability, and irradiation temperature, stress, and neutron energy spectrum. Various improvements have been made in the performance of 316 stainless steel, but the alloy has inherent limitations which preclude the attainment of lifetimes of 120-150,000 MWd/T. Recognizing this, in 1974 the U.S. initiated a disciplined, highly-structured alloy development program which has produced alloys with much potential for improved component performance. Materials under development include modified 316 SS, precipitation strengthened alloys, and ferritic alloys.

The modified 316 stainless steel alloy recently selected for further development is of most immediate interest, because it represents a minor departure from the technology developed for the reference material while at the same time offering greatly improved swelling and creep resistance. Use of this material in breeder reactor fuel systems will yield substantial improvements in overall fuel system performance. Even greater performance improvements are considered to be offered by the precipitation-strengthened alloys, which provide much greater high temperature strength and improved swelling and creep resistance. Large-scale introduction of these alloys is anticipated as ongoing experiments are completed. This work includes refinement of fabrication methods to gain consistent yields of high-quality product forms and the development of means to improve the ductility of these materials under transient loading conditions. The third alloy class, the ferritic steels, has the very attractive property of extremely low swelling and irradiation creep rates. It remains to ensure that these materials will not behave in a brittle manner at refueling temperatures.

Plutonium fuel fabrication technology is undergoing revolutions to assure secure automated fabrication, storage and shipment, plus improved in-reactor performance. More than 15 million mixed uranium-plutonium oxide fuel pellets have been fabricated using conventional glovebox technology. As illustrated in Figure 5, an advanced Secure Automated Fabrication (SAF) system is being developed in the U.S. for uranium-plutonium oxide fabrication. This system will minimize personnel radiation exposure and provide the best possible safeguards while decreasing fuel fabrication costs and assuring better fuel performance from more accurate process control.

In conclusion, the long standing U.S. goal of assuring a safe, safeguarded and economic breeder reactor technology is succeeding and is providing anticipated data on a wide range of fuels and materials. This effort culminates with a pipeline of exciting data which are now forthcoming from EBR-II, TREAT, and particularly FFTF in the U.S., supplemented by much larger scale operations of power producing breeder reactors in other countries. It requires this range of efforts and different approaches in various countries to give us the greatest assurance of both safe and economic breeder reactors and, above everything else, it behooves us to find and capitalize on the synergism possible from these ranges of widely differing but equally intense, dedicated efforts. The remarkable performance of the tiny ceramic fuel pellets which lie at the heart of any of these reactor systems should provide inspiration and confidence that the overall systems will soon be operating far more reliably than the most optimistic have predicted. In the decade just starting, these proven systems can be subjected to the necessary political and institutional considerations which will then determine the crucial point at which we can cash in on the breeder option.

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REACTOR DEPLOYMENT

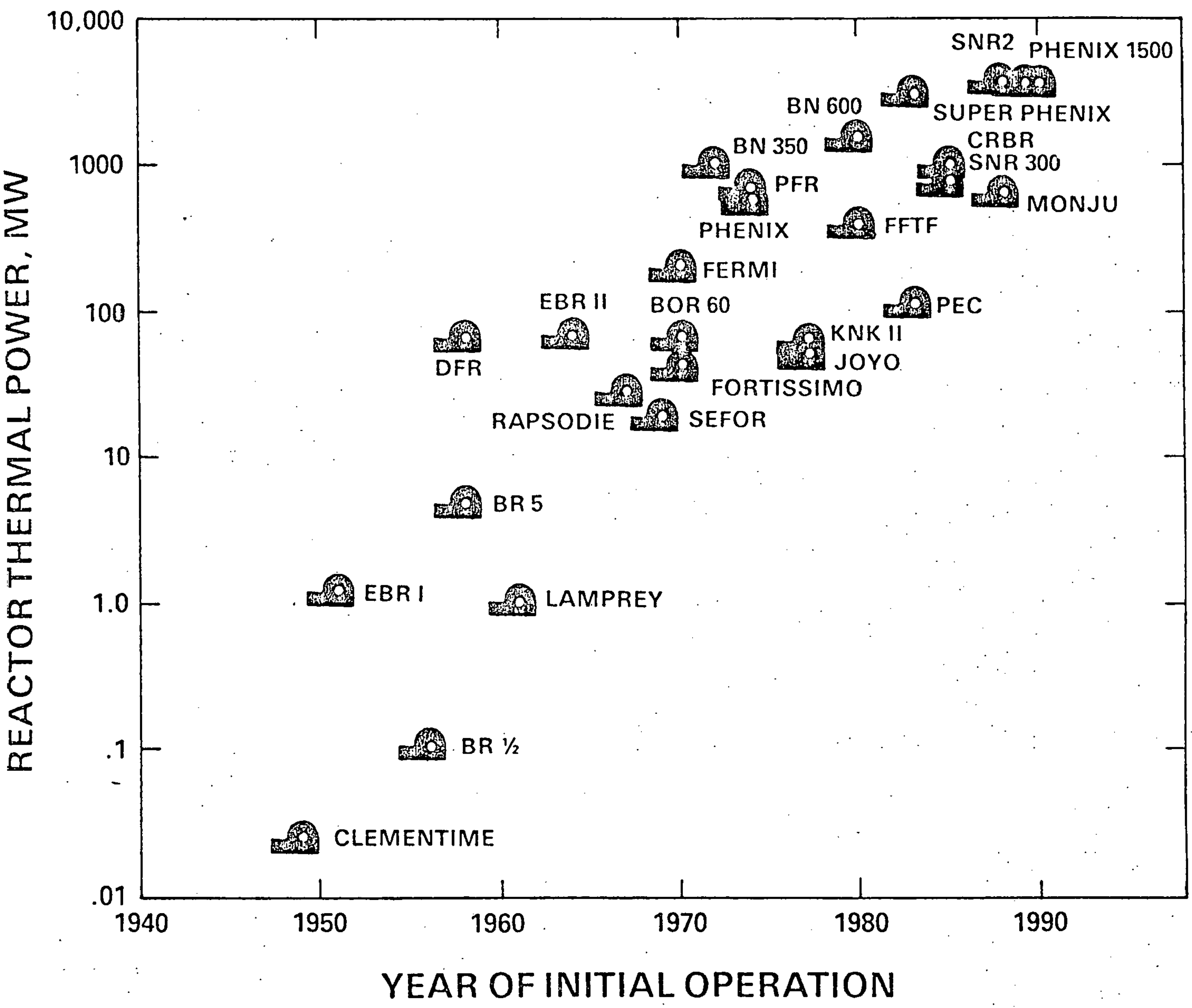

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FIGURE 1

FUEL ASSEMBLY SIZE EVOLUTION

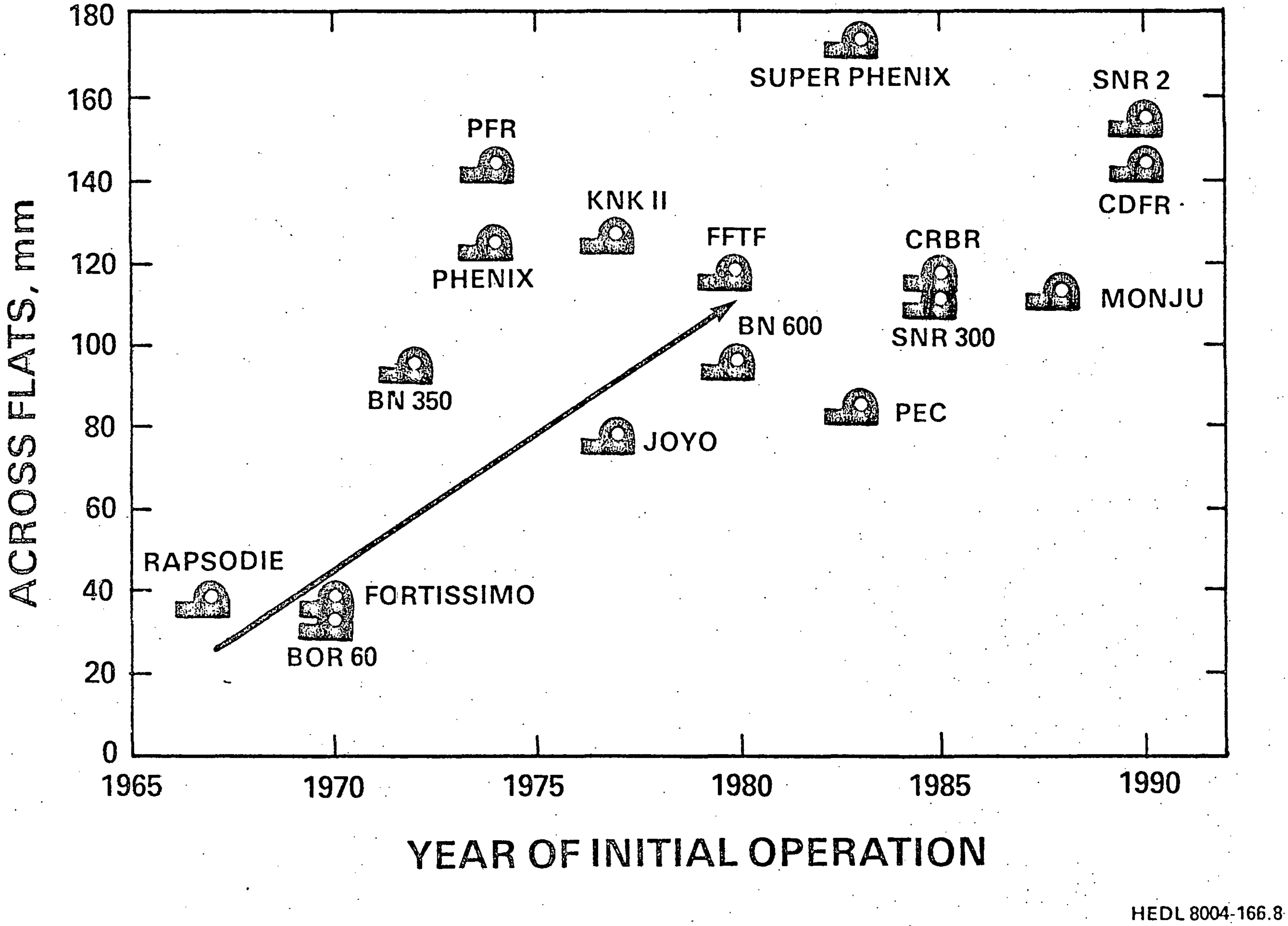

FIGURE 2

LMFBR OXIDE PINS IRRADIATED WORLDWIDE

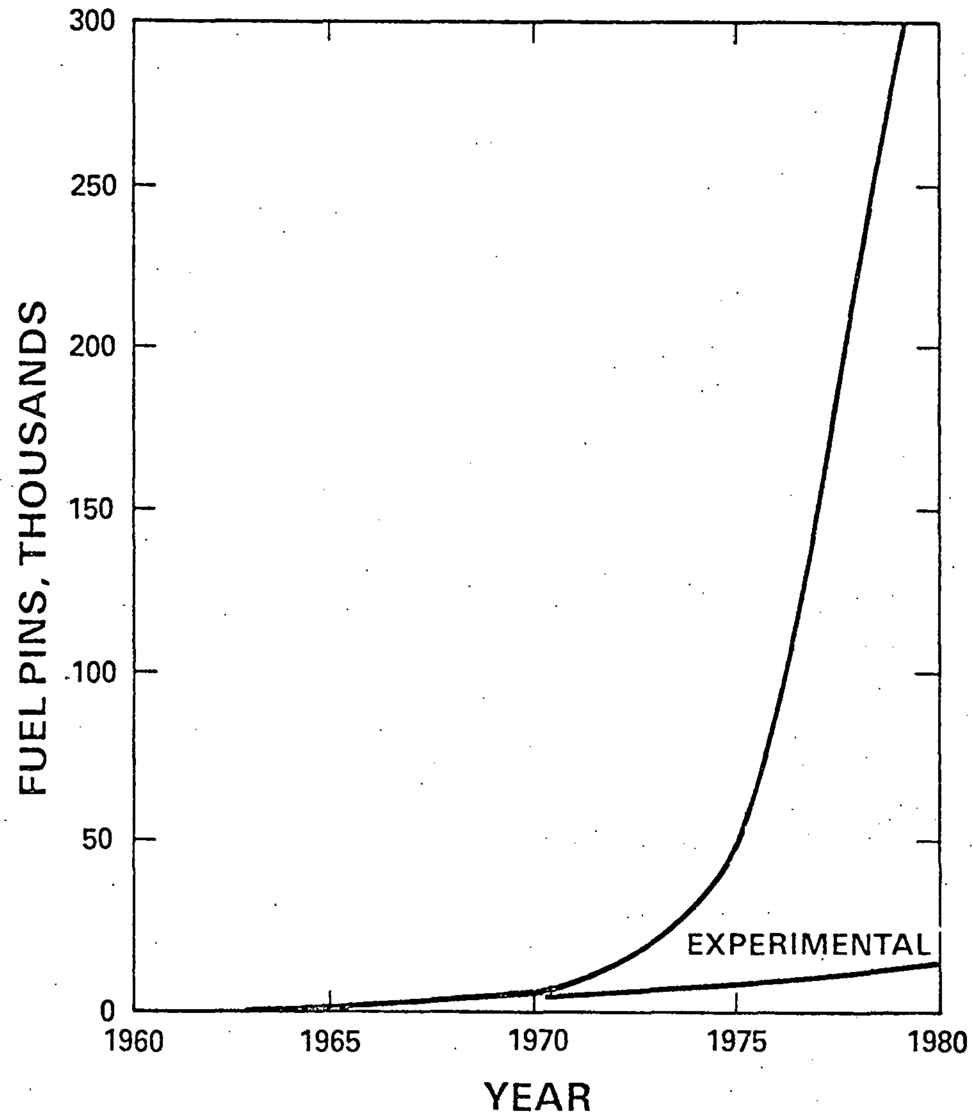

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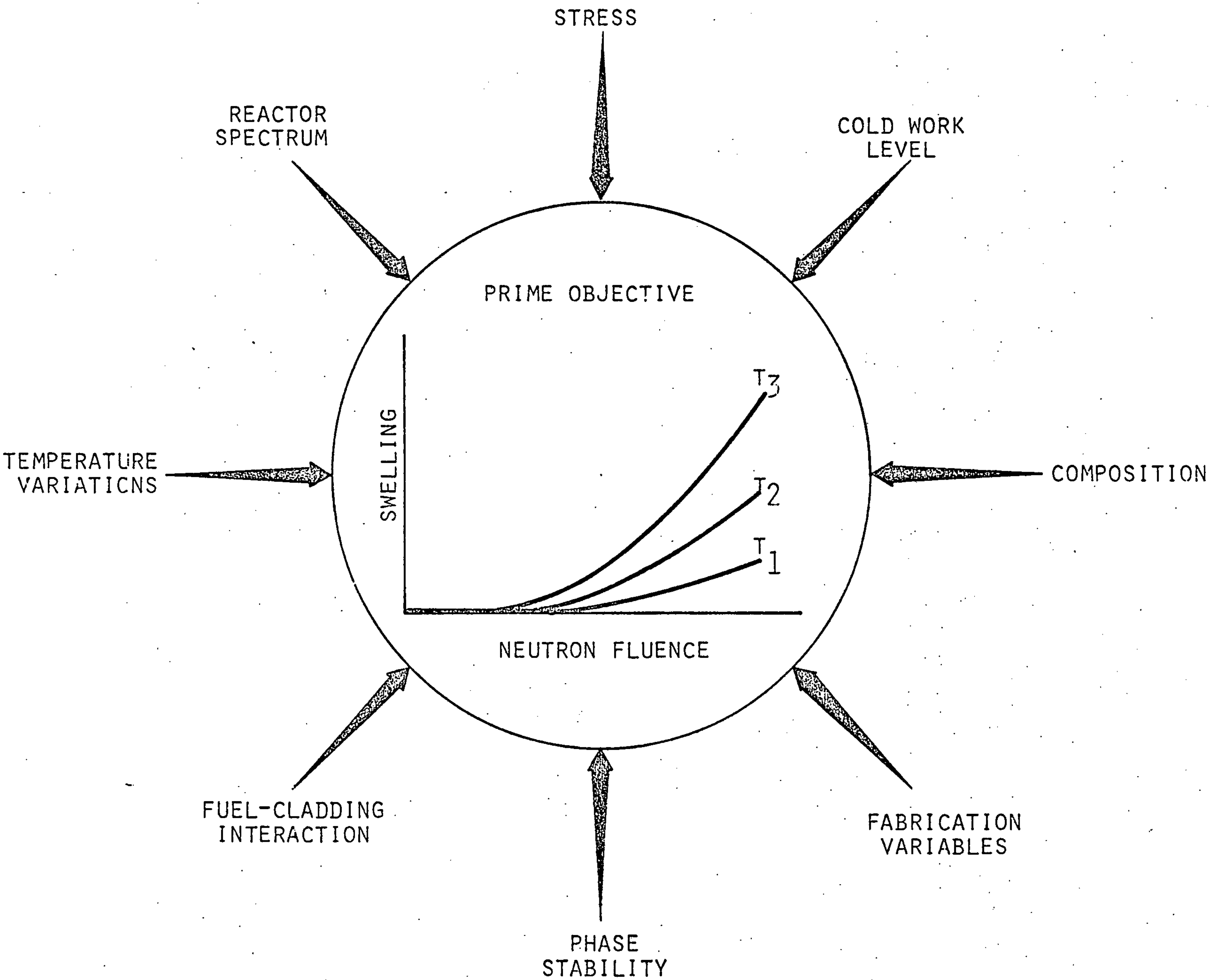
FIGURE 3



FACTORS INFLUENCING SWELLING

FIGURE 4

SECURE AUTOMATED FABRICATION (SAF)

- FABRICATION LINE
  - AUTOMATED
  - REMOTELY OPERATED
- SUPPORT SYSTEMS
  - NUCLEAR ACCOUNTABILITY
  - CHEMICAL ANALYSIS
  - WASTE & SCRAP HANDLING
  - EQUIPMENT MAINTENANCE
- FACILITY
  - PROTECTIONS FROM DIVERSION
  - PROTECTIONS FROM WEATHER

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TABLE I

PERFORMANCE OF THE U.S. REFERENCE MIXED-OXIDE FUEL DESIGN

Performance Issue	Results of Testing Program (EBR-II)
1. Thermal Performance	• Power-to-melt increases approximately 20% compared to fresh fuel due to early-in-life gap closure, i.e., fuel restructuring. • High burnup power-to-melt similar to fresh fuel.
2. Solid and Volatile Fission Products	• No detrimental effects due to solid or volatile fission products. • Cesium migration occurs and increases with decreasing O/M. • Cesium reactions with fuel and insulators noted with corresponding cladding strain without breach.
3. Fuel Stability and Consistent Migration	• Fuel columns exhibit excellent dimensional stability. • Observed plutonium relocation could result in approximately 5-percent reduction in power-to-melt.
4. Fuel-Cladding Chemical Interaction	• Increases with increasing temperature and burnup but significantly reduced by lowering the O/M ratio. • Has not caused a cladding breach.
5. Cladding Breaches	• Breaches are very small and non propagating and have no observable influence on neighboring pins.
6. Cladding Performance	• Pin diameter increases with fluence due to cladding swelling and creep. • Sodium cladding corrosion decreasing with times to 11,000 hours and is much less than design allowance.
7. Fission Gas	• Gas release approaches 100% at more than 8 a/o burnup.
8. Overall Performance	• EBR-II testing demonstrates that the reference fuel system can successfully achieve goal peak burnups of 80 MWd/Kg.