The U. S. Advanced Neutron Source

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The ANS project

The Advanced Neutron Source (ANS) is to be a new user experimental facility for all fields of neutron research. The most important scientific justification for the ANS Project[1,2] is to provide intense beams of neutrons for scattering and other experiments: neutron scattering is a primary tool of basic and applied materials science. Facilities will also be provided for engineering materials irradiation tests, isotope production (including transplutonium elements), and materials analysis. More than 1000 users per year are expected to carry out experiments at the ANS facility.

The source of neutrons will be a steady-state reactor designed to maximize the thermal neutron flux available outside the core, where it is accessible to neutron beam tubes and guides.

The objectives of the ANS Project are:

1. to design and construct the world's best research reactor for neutron scattering;
2. to provide isotope production facilities that are as good as, or better than the High Flux Isotope Reactor (HFIR); and
3. to provide materials irradiation facilities that are as good as, or better than, the HFIR.

   In addition to these objectives, certain constraints have been placed on the reactor designers. Specifically, safety issues and technical risks are to be minimized by basing the reactor as far as possible on known technology; in particular, the design should not rely on the development of new technology to meet the minimum design criteria. However, research and development (R&D) work that could lead to further major improvements in performance will be identified and planned. Furthermore, a high availability of the reactor should be provided to users. This constraint implies a minimum core life of about 14 d that, in conjunction with an average shutdown of 3 d/cycle or 65d/year, would give an availability of more than 80%.

The major design criteria for the ANS reactor (ANSR) are set by the user needs (Tables 1 and 2). The neutron beam experimenters, for example, want the highest possible flux of slow neutrons with a minimal contamination of the beam by fast particles. For irradiation testing of structural materials, especially for the fusion program, the opposite is required: a high fast flux with little thermal neutron content.

Table 1. User requirements in six major fields of neutron research: neutron flux and spectrum characteristics

	Hot/thermal/cold	Epithermal	Fast
Neutron beam experiments	High		Low
Isotope production	High		
Materials analysis	High		
Transuranium production	Medium	High	
Fuels irradiation	Medium		Medium
Structural materials irradiation	Low		High

Table 2. User design criteria for the ANS

Parameter	Minimum criteria
Peak thermal flux[a] in reflector	≥ 5
Thermal/fast ratio	≥ 80
Thermal flux at cold source position	≥ 2
Epithermal flux for transuranium production	≥ 0.6
Epithermal/thermal ratio	≥ 0.25
Thermal flux for isotope production	≥ 1.7
Fast flux for small materials tests	≥ 1.4
Fast/thermal ratio	
Fast flux for larger tests	≥ 0.5
Fast/thermal ratio	≥ 0.3

[a] All fluxes in units of 10^{19} neutrons/(m^2s^{-1}), or 10^{15} neutrons/(cm^2s^{-1}).

Beam reactor design

Nuclear reactors produce large numbers of neutrons, ~8 x 10^{16} neutrons/s for each megawatt of thermal power. These neutrons are born, within the core, with an energy of a few MeV, that is, they are fast neutrons. If the reactor core is small and does not contain an effective moderator material, most of these fast neutrons will escape into the surrounding medium, still with a high energy. If the surrounding medium is also a poor moderator and not an absorber, the fast neutrons will eventually be moderated down to thermal energies some distance outside the core. Some of these thermal neutrons will diffuse back into the core, maintaining the chain reaction; for this reason, the region outside the core is referred to as the reflector. Such a system has a high fast flux inside the core region and a high thermal flux some way outside it, with a volume of high epithermal flux in between. A reactor of this kind can simultaneously meet, in different zones, the seemingly conflicting requirements of the various user groups listed in Table 1.[3]

This design for a high flux beam reactor is typified by the world's most advanced neutron-scattering facility, the Institut Laue Langevin (ILL) at Grenoble, France. The ILL reactor core is a compact annulus of aluminum-clad fuel plates occupying a volume of only about 46 L. The core is cooled by heavy water (a relatively poor moderator with low absorption), and the reflector is a large tank of heavy water surrounding the core. the power level is 57 MW, and the peak thermal flux—found in a region about 130 mm outside the fuel element—is ~1.5 x 10^{19} neutrons/m^2s^{-1}.

Technology for the ANSR

As indicated above, the secret of a high flux beam reactor is a small, high-power core in a low-absorption, low-moderation environment (perhaps 300 MW in a 40-L core, cooled and reflected by D_2O for the ANSR). To build such a system, we require a fuel geometry that puts a large cooling surface in a small volume and also a high-density fuel form so that sufficient fissile material can be loaded to maintain criticality for at least 14 d at full power. The core design should optimize the thermal flux and spectrum in the reflector, while maintaining acceptable conditions of neutron flux and spectrum with acceptable gamma heating rates in the structural materials.

Fortunately, the required technology is found in the HFIR, at ILL, and other existing reactors or has been developed since those reactors were built. Thus, the annular, involute element of aluminum-clad, cermet fuel plates has been used with complete success for the past 20 years in the HFIR and at ILL (Table 3 and Fig. 1).

Table 3. Compact annular fuel elements similar to the ANSR design and used with complete success for 20 years on other reactors

Reactor	Fuel-plate thickness (mm)	Cladding thickness gap (mm)	Coolant channel length (mm)	Plate axial
ILL	1.27	0.38	1.80	880
HFIR	1.27	0.25	1.27	610
ANSR	1.27	0.25	1.27	235

The ANSR coolant and reflector will be heavy water; ILL and the High Flux Beam Reactor (HFBR) at Brookhaven are among the many research reactors that already use this technology.

The coolant velocity in the ANS reactor may be 27 m/s, only 23% greater than the 22 m/s that has been used at the Savannah River Plant; furthermore, experiments at Savannah River revealed no erosion problems for aluminum plates up to 30.5 m/s. The fuel form selected, in the reference design, is U_3Si_2, which has been developed by Argonne National Laboratory and extensively tested in U. S., European, and Japanese reactors. In Fig. 2, the area to the left of and below the solid line is considered to be the "known region" of fuel loading and burnup, whose characteristics have been demonstrated by tests: the range of conditions expected within the ANSR, shown by the cross-hatched region, lies within the known region. However, special tests will be needed to verify that the fuel behavior is as expected under the very high rate of burnup expected in the ANSR.

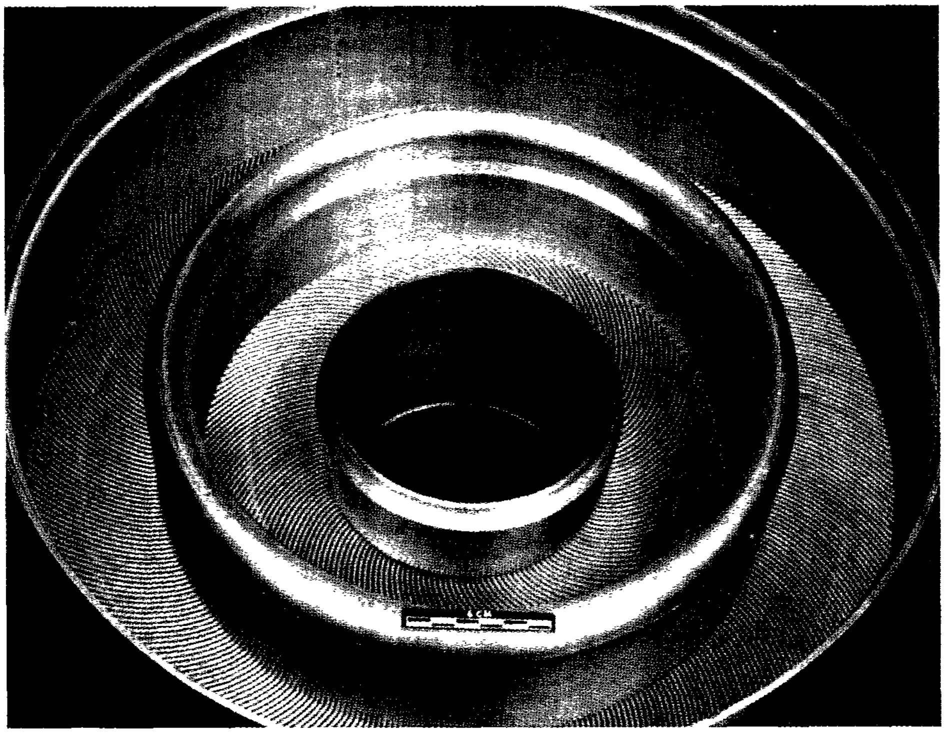

Fig. 1 Involute (HFIR) fuel element.

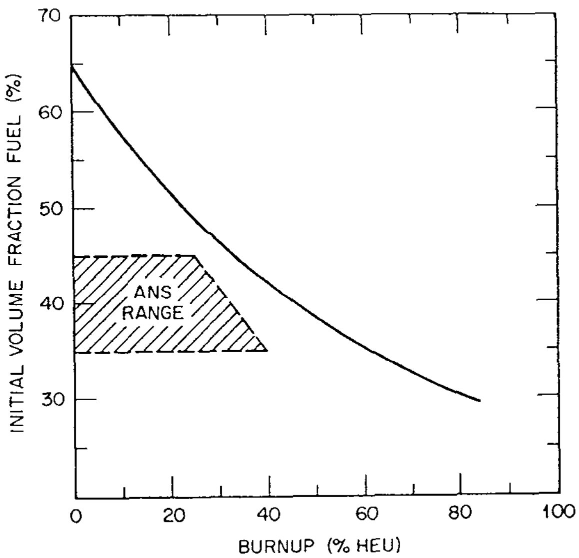

Fig. 2 Burnup and volume fraction of U_3Si_2 fuel.

The core is formed in two elements, separated by a heavy water gap. Compared with a core without the central gap, this arrangement (Fig. 3) provides efficient neutron production and reduces the gamma and fast neutron flux on the midplane. There are also some safety advantages. The National Institute of Standards and Technology reactor in Washington, D. C., already has an axially split core, and such a design is also proposed as an upgrade to the Jülich heavy water research reactor.

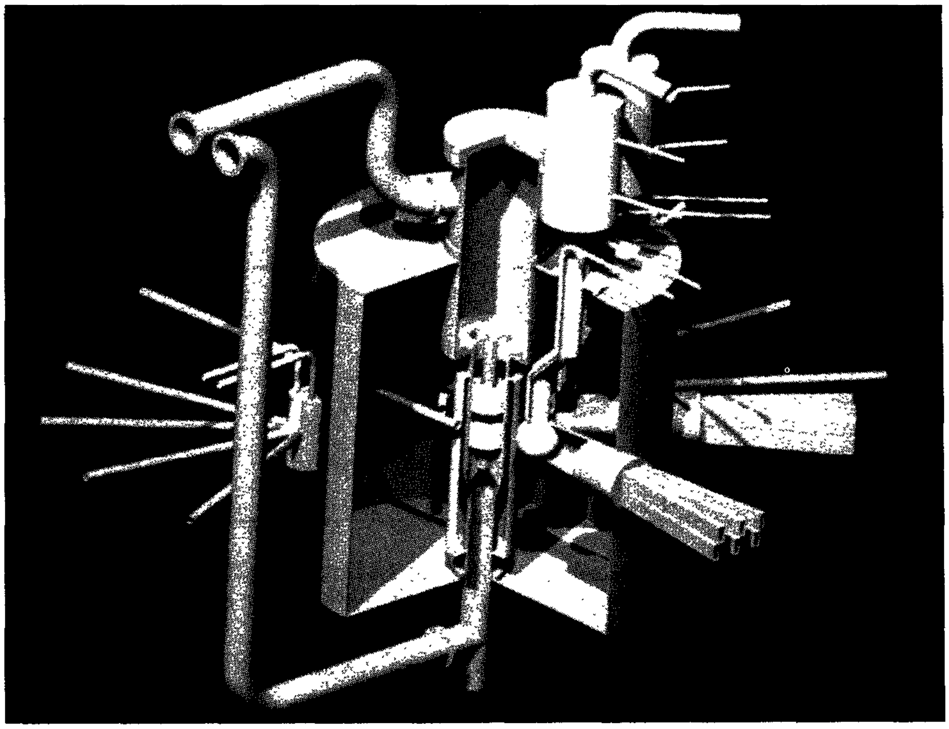

Fig. 3 Reactor core and reflector tank assembly with cold sources.

Reactor safety

The ANS Project intends to maximize inherent safety features of the reactor. For example, the large Department of Energy (DOE) reservation at Oak Ridge permits the reactor to be placed further from the site boundaries than even much larger power reactors. Compared with a typical power reactor, the low power level and fuel loading of the ANSR lead to a smaller fission product inventory and decay heat sources (Table 4). A large containment volume is needed to provide space for beam experiments, and this large volume (>100 m^3/MW of thermal power compared with only ~10 m^3/MW for a typical light-water power reactor) is a significant safety feature. Unlike a power reactor, the ANSR will be designed so that the coolant is below 100°C, so in the event of a pipe rupture the water will not flash into steam and challenge the containment integrity. Other features include the small core, which limits the chemical energy available to drive an accident, and the large light-water shielding pool, which is an effective heat sink for accident mitigation and also would retain a large fraction of any fission products released below its surface. The relative simplicity of a research reactor, compared with an electrical generating plant, is also a safety advantage. The high power density of the core, however, means that the time available to reestablish core cooling under emergency conditions is less than that for a power reactor; thus, emergency core cooling is an especially important issue.

Table 4. Power levels and radionuclide inventories[a]

Reactor	Operating power [MW(t)]	Fuel mass (kg)	Radionuclide[b] inventory (10^7 Ci)[c]	Decay heating rate at various times after shutdown (MW) 50s	10,000s
HFBR	60	12.4	2.1	2.7	0.5
EBR-II	62.5	345	7.6	2.3	0.6
HFIR	85	11.9	4.3	2.8	0.6
ATR	250	39-46	24	12.6	2.4
ANSR	**300**	**25-30**	**9.0**	**9.9**	**2.2**
FFTF	400	2,928	31	20	
PWR[d]	3,414	101,100	160	100	26
Savannah River[e]	2,915	113,000	220	154	63

a Data for reactors other than the ANS are taken from Table 1 of *Safety Issues at the DOE Test and Research Reactors*, National Academy Press, Washington, D. C., 1988

b Radiologically important isotopes of Kr, Xe, I, and Cs calculated at shutdown for refueling.

c 1 curie = 3.7 x 1010 becquerel.

d Typical commercial pressurized-water reactor.

e Savannah River production reactor at full power.

The ANS Project has, from the beginning, taken a proactive approach to safety. The Safety Analysis Manager, even at the early stages when design detail was insufficient to carry out extensive calculations, was at the same management level as the R&D and Engineering managers, reporting to the Project Director. A safety philosophy was established early in the preconceptual design phase, documented (as a living draft), and widely distributed to project staff.

The design is based on the proven strong points of existing reactors and especially those of the HFIR, which has recently undergone multiple, extensive safety reviews. The ANSR design is fully responsive to the findings of those reviews.

A Probabilistic Risk Assessment (PRA) was initiated in the preconceptual design phase and has already led to design changes that will enhance safety. The use of PRA to influence design at the preconceptual stage is unique and will continue throughout the design effort.

The containment design has a low-leakage, steel inner dome, separated from the hardened concrete outer dome by a ventilated plenum that exhausts through high-efficiency particulate air (HEPA) and charcoal filters (Fig. 4). With design criteria (outleakage from the inner containment of not more than 4%/d and removal of at least 99% of iodine from the outleakage by the filters) that are well within the current state of the art, the region for mandatory evacuation in case of the maximum postulated accident is entirely within the DOE reservation (Fig. 5).

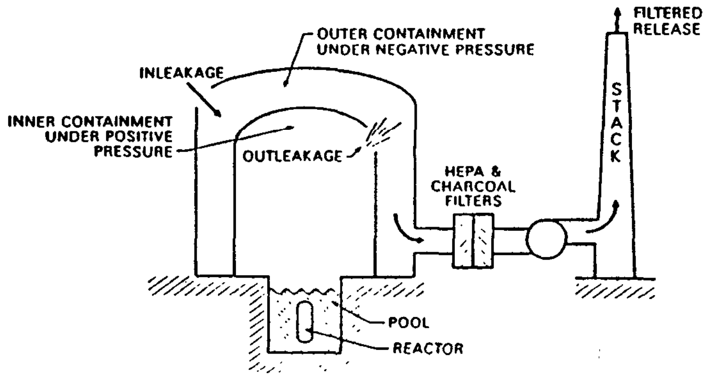

Fig. 4 Double containment with ventilated outer containment.

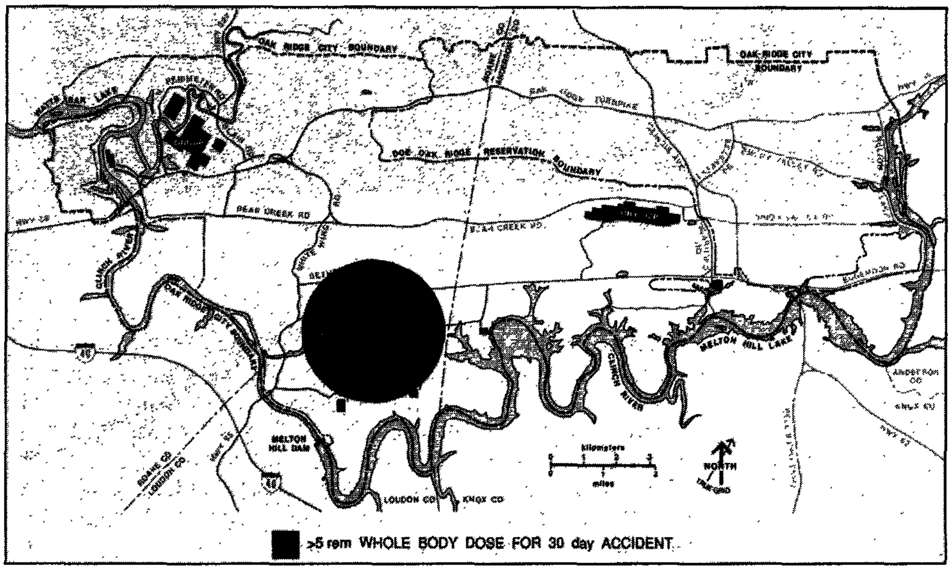

Fig. 5 Region for mandatory evacuation in case of maximum postulated ANS accident is entirely on the DOE reservation at Oak Ridge.

Site layout

The facility architecture effectively separates the experiment areas from reactor operations areas. This approach provides control of personnel and contamination and makes it possible to establish appropriate security and ventilation zones. Noise and vibration control in experiment areas is also enhanced by separating the reactor coolant pumps and main heat exchangers from the neutron-scattering instruments.

A computer drawing of the facility layout is shown in Fig. 6. The main entrance lies between, and provides access to, the office building (which includes accommodation for the users) and the experimental guide hall. A security control center is located in the entrance area through which experimenters can be given access to the experimental floor in the reactor building and authorized personnel can be admitted to the reactor operations areas.

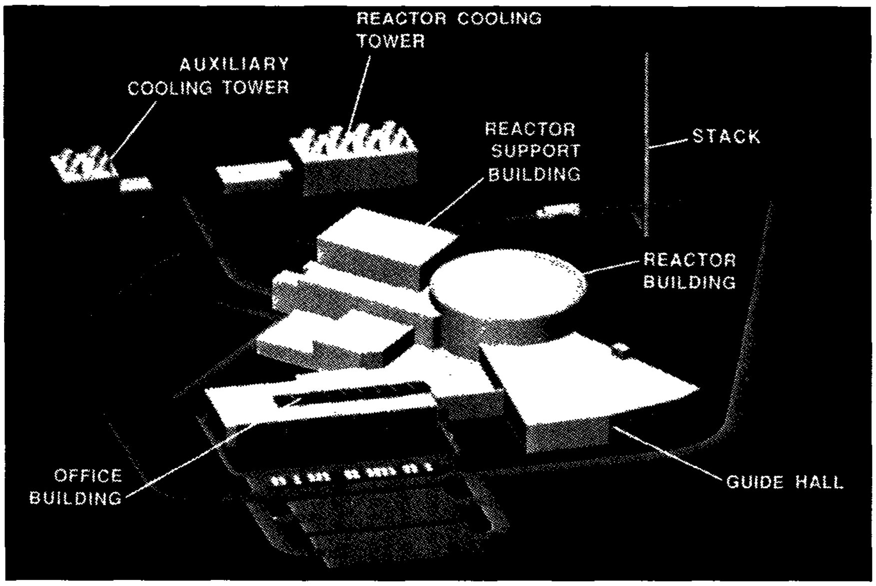

Fig. 6 Perspective of ANS facility.

Fuel enrichment

Existing DOE orders address the physical protection of fissionable material and critical facilities. The sections of those orders relevant to the ANS Project do not distinguish between highly enriched and medium-enriched uranium fuel (HEU and MEU); that is, the precautions are no less stringent for MEU than for HEU. Low-enrichment fuel (LEU) could be stored, transported, and handled with fewer precautions. However, for the particular case of the ANSR located at Oak Ridge, the use of HEU poses very little extra cost for security and safeguards because the systems for transport and storage of weapons-grade material are already in place to support the Y-12 weapons component production plant in Oak Ridge. With these systems available, the extra cost of secure shipment of HEU for the ANSR would be only about $100,000 per year, and the additional cost for security forces to provide protection during refueling would be \$10,000 to \$100,000 per year.

Even for licensed research reactors, Nuclear Regulatory Commission (NRC) rules[4] (which do not presently apply to DOE facilities) provide for the use of highly enriched fuel where necessary to meet a "unique purpose." Examples given by NRC of unique purpose include "research projects based on neutron flux levels or spectra attainable only with HEU fuel," and "a reactor core of special design that could not perform its intended function without using HEU fuel." The ANSR falls in this category. For example, at 300 MW an HEU core will give ~65% more flux than an LEU one; the flux from HEU will be 5 to 10 x 10^{19} neutrons/m^2s, but from LEU only 3 to 6 x 10^{19} neutrons/m^2s. The additional cost of raising the power level to regain the flux lost by going from HEU to LEDU is \$100 million inconstruction, and \$400 million in lifetime fuel and pumping power costs: these costs should be compared with the \$100,000 per year cost of providing security and protection for the HEU fuel. Furthermore, the higher power level of the LEU core brings the safety disadvantage of a much higher fission product inventory decay heat load. The present reference design therefore incorporates HEU as presently used at the other reactors in Oak Ridge.

Performance specifications

The major performance parameters of the reference core are compared with the user design criteria in Table 5. Because the core design is still evolving in some respects the figures shown are approximate; nevertheless, it is clear that the design concept can meet and in most cases greatly exceed the minimum requirements of the user community.

R & D tasks

"Feasibility R&D" addresses some basic assumptions about the behavior of certain components and materials that have so far been tested only under conditions that are less demanding than the ANSR. One example, mentioned previously, is the fuel behavior at high fission rates. Other examples include the fuel clad oxidation rate at very high heat flux and the thermal-hydraulic and structural stability of the involute core assemblies. In addition, further preconceptual design work is needed to establish the design criteria so that conceptual design can begin; for example, the control concepts, cooling system, site selection, facility and experimental instrument layout, and safety criteria must all be finished, or at least frozen, before conceptual design can begin.

Among the R&D areas identified as offering the potential for further major improvements in performance are (1) reduction of fuel clad corrosion rate, perhaps by surface modification, choice of materials, or water chemistry manipulation; (2) improvements in neutron mirror and neutron detector technology; and (3) enchancement of core cooling by introducing fresh coolant that has bypassed the first fuel element into the inlet of the second element in the gap between the two core halves.

Table 5. Approximate major performance parameters of the February 1988 reference core compared with the user design criteria

Parameter	Minimum criteria	Reference core[a]
Peak thermal flux in reflector[b]	> 5	10
Thermal/fast ratio	> 80	80
Thermal flux at cold source position	> 2	8
Epithermal flux for transuranium production	> 0.6	2
Epithermal/thermal ratio	> 0.25	2
Thermal flux for isotope production	> 1.7	4
Fast flux for small materials tests	> 1.4	6
Fast/thermal ratio	> 0.5	6
Fast flux for larger tests	> 0.5	1
Fast/thermal ratio	> 0.3	0.4

[a] Unperturbed at nominal power level

[b] All fluxes in units of 10^{19} neutrons/(m^2s^{-1}), or 10^{15} neutrons/(cm^2s^{-1}).

Schedule and cost

Figure 7 shows the schedule that forms the project's current planning base. This schedule calls for congressional approval (and funding) to begin detailed design work in FY 1992, followed by approval and funding for construction to begin in FY 1993. The reactor would first go critical at the end of FY 1997. This is almost the fastest schedule that can now be imagined, and of course it depends upon timely availability of the funding for these activities, described in the previous section, that must precede conceptual and detailed design.

The spending plan associated with this schedule is presented in Fig. 8: the costs of detailed design and construction are presently estimated at $412 million (1988 dollars), but until a conceptual design is completed, no validated construction cost estimate can be made.

Summary

A reactor design based on previously developed technology can meet the minimum, and at least approach the maximum, performance criteria set by the user community for the ANS. The design approach, objectives, and organization of the ANS Project emphasize safety and minimize technical risk. Certain R&D issues that must be resolved to give full confidence that the design will meet performance criteria have been identified and are being addressed. Other R&D tasks that might further enhance performance or safety margins have been identified and are being addressed.

Acknowledgements

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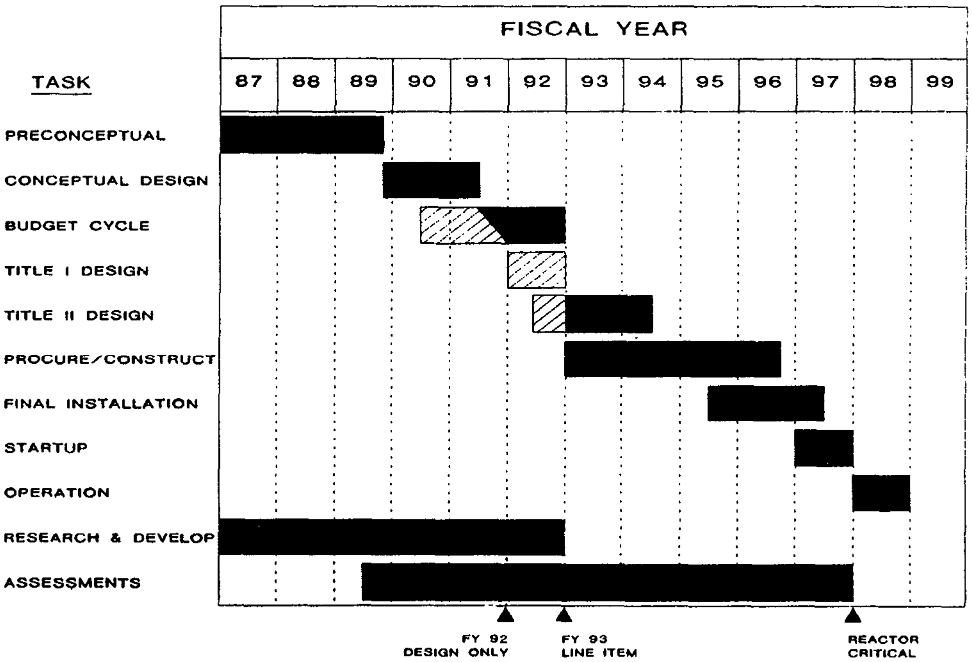

Fig. 7 Schedule for ANS project.

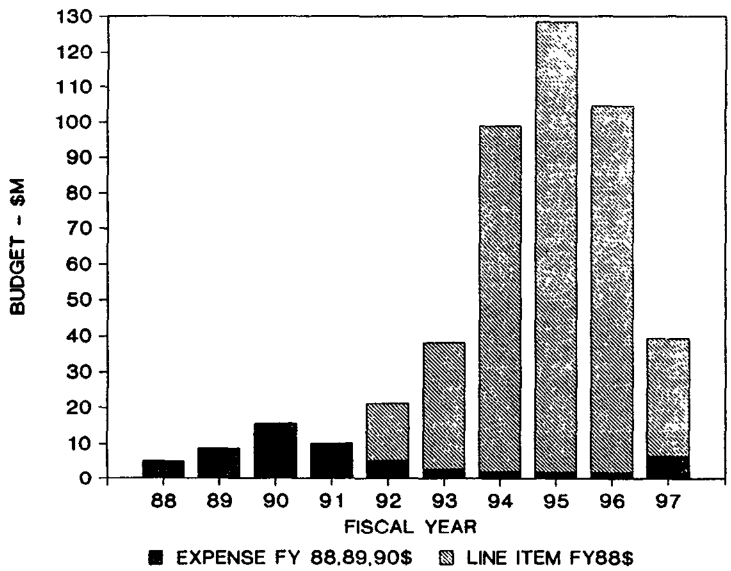

Fig. 8 ANS project spending plan.

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