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SP-100 PROGRAM

Technical Information Report

SP-100, A Project Manager's View

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National Aeronautics and
Space Administration

JPL

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

MASTER

SP-100 PROGRAM

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Washington, D.C.

Jet Propulsion Laboratory
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SP-100, A Project Manager's View *

INTRODUCTION

Born to meet the special needs of America's space effort, the SP-100 Program testifies to the cooperation among government agencies. The Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), and the Defense Advanced Research Projects Agency (DARPA) are working together to produce a 100-kW power system for use in outer space. At this point in the effort, it is appropriate to review: the approach to meet program goals; the status of activities of the Project Office, managed by the Jet Propulsion Laboratory (JPL); and, because this is a meeting on materials, answers being developed by the Project Office to vital questions on refractory alloy technology.

APPROACH

Four major milestones (Fig. 1) emerge for the SP-100 Program. The Memorandum of Agreement between the three government agencies, which really kicked off the current phase of the effort, was completed in the second quarter (February) of FY 1983. Approximately a year from that date the concept(s) will be selected. The final milestone is tentatively set for the fourth quarter (July) of FY 1985. At that time we will recommend to the Program Office which concept ought to go forward, what technologies ought to be utilized, and whether or not to begin ground testing. To determine if we are on track and to ensure that we can make a ground test decision in FY 1985, the program will be reexamined in mid-1984. At that

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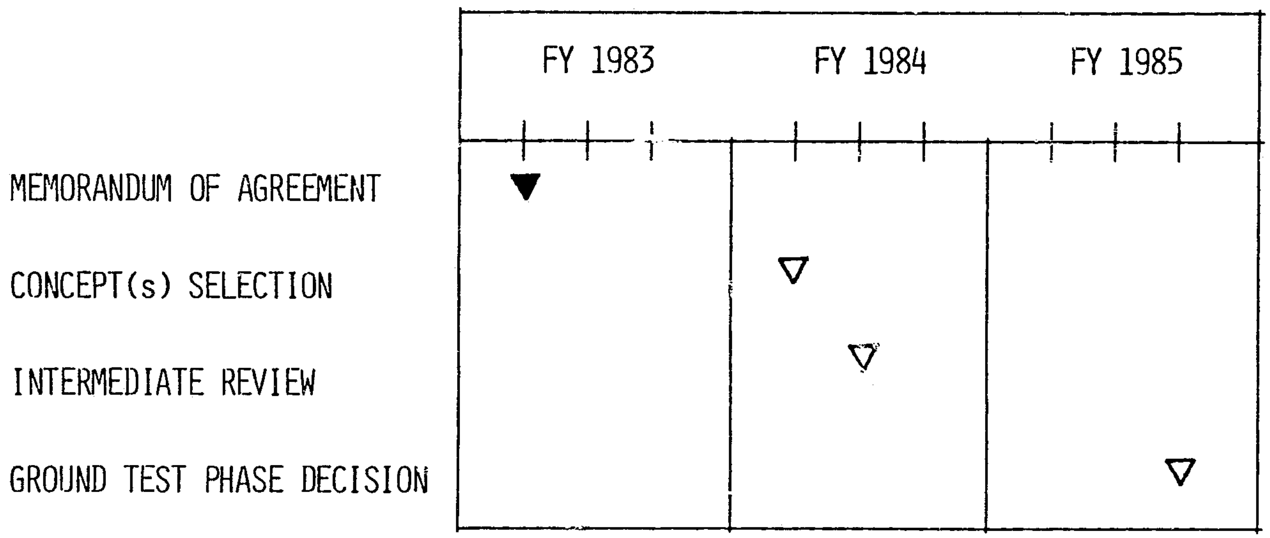

Fig. 1. Major program milestones.

point we should be prepared to determine if we will need more time, if we can make the decision by late FY 1985, or (and this is less likely) if we can do it sooner.

The program will probably go through three phases: phase 1, technology assessment and advancement; phase 2, ground testing, in which we will actually build and demonstrate hardware on the ground; and phase 3, flight qualification. In actuality, phase 3 may not take place. Other nuclear space programs, such as the radioisotopic thermoelectric generator program, went from ground demonstration directly into a flight program. We do not know, however, if that is a good idea for larger systems. Our systems contractor will examine the issue and advise us. Right now the program is in phase 1, the two- to three-year technology assessment and advancement stage. What then are our current objectives?

Briefly, the goals of phase 1 are (1) concept definition, (2) technical feasibility, and (3) costs and schedule development. The first goal, concept definition, includes understanding what the missions are. A number of missions are enabled or made possible with the use of a reactor system, and a large part of our program is dedicated to trying to understand these missions and what their requirements are. A complementary aspect is then determining which systems make the most sense and can best meet those particular requirements. Identifying the missions and the concepts provides a fair understanding of what technological issues have to be answered before we can enter the ground testing phase of the effort.

Not only do we identify the technical issues but we carry out experiments and analyses. Our second goal is to conduct those development activities required to address these issues and resolve them enough to satisfy ourselves they will not affect the technical feasibility of the concept. What do we mean by enough? Very simply, we mean looking hard enough at each of these technological issues that once we select a particular concept and a particular set of technologies, materials, or what have you, we will not embark on phase 2 and suddenly find that we have to stop. Reasons for stopping would include discovering a major "show-stopper"; the need for a major development effort; or that we cannot use the concept, materials, or conversion devices initially selected. We must move into the ground demonstration phase with a high probability of completing the engineering development.

The third important goal is understanding costs and schedule. Before we can get any sponsor to fund the second and third phases of the program, we must have a thorough understanding of costs. In the present phase, we are talking about an effort in the order of $15 million a year, or a total of about $45 million to $60 million before we move into phase 2. Obviously the ground demonstration phase of the effort is going to be much more expensive, hundreds of millions of dollars each year. We could be talking about a total cost of a billion, or even several billion, dollars. Before any sponsor — or even Congress — would commit to such funding, we must have a good comprehension of the costs and schedule for completing these next phases. Will development take two or three years and $0.5 billion to $1 billion or five or six years and $5 billion to $6 billion? Our system contractors and in-house efforts are going to be aimed to a large extent at trying to understand this question. We are under pressure to generate these kinds of numbers, because both NASA and DOE must begin to put them into their budgets for subsequent years.

STATUS

What is the status of the SP-100 Program? First, it is already organized and structured (Fig. 2). The Project Office includes the manager, assistant manager, and two deputies — one for Nuclear Technology and one for Aerospace Technology. A coordination team established to integrate program resources and responsibilities include representatives from Los Alamos National Laboratory (LANL), JPL, and the NASA-Lewis Research Center (NASA-LeRC). They coordinate efforts, not only of these three laboratories but of other support organizations as well [for example, DOE laboratories such as Oak Ridge National Laboratory (ORNL) and Hanford Engineering Development Laboratory (HEDL) and possibly other NASA centers].

The program itself is divided into four major areas. The Mission Analysis and Requirements and System Definition areas are each headed by a manager. The Aerospace and Nuclear Technology areas are managed by the Project Office deputies. Another area vital to the project and its viability is Nuclear Safety. Obviously, to get launch approval, quite a few safety issues will have to be surmounted. Though the Nuclear Technology manager is responsible for this important area, we also have a Safety Advisory Committee (Table 1), which has begun evaluation of our activities (Table 2).

The first major area, Mission Analysis and Requirements (Fig. 3), is divided into planetary missions, military missions, space station activities, and civilian and commercial missions. In-house activities at NASA-LeRC and JPL as well as contracted activities through the military

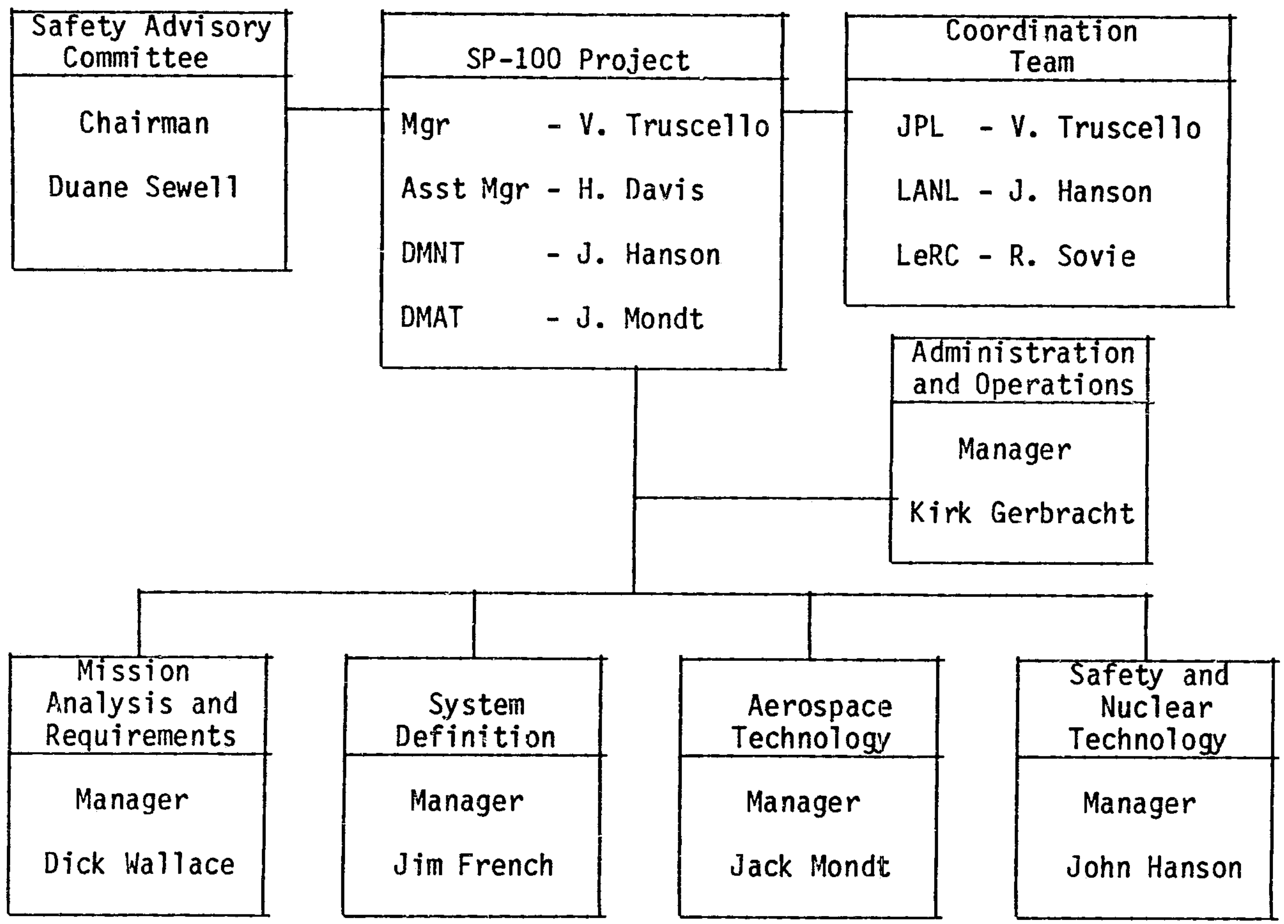

Fig. 2. SP-100 Program structure.

Table 1. Members of the SP-100 Project Safety Advisory Committee

Name	Affiliation
Duane Sewell (Chairman)	
Robert Bacher	California Institute of Technology
Garth Cummings	Lawrence Livermore National Laboratory
R. E. Schreiber	
A. W. Snyder	Sandia National Laboratory
James Lee	United States Air Force
Dave Okrent	University of California (LA)
Stanley M. Luczkowski	Johnson Space Center
Milton S. Plesset	California Institute of Technology

Table 2. Status of Nuclear Safety activities

- Two meetings held by advisory committee
- Preliminary safety plan completed and reviewed by advisory committee
- Preliminary safety design requirements completed and reviewed by advisory committee; requirements issued to system contractors
- Coordination with interagency nuclear safety review panel (INSRP) begun

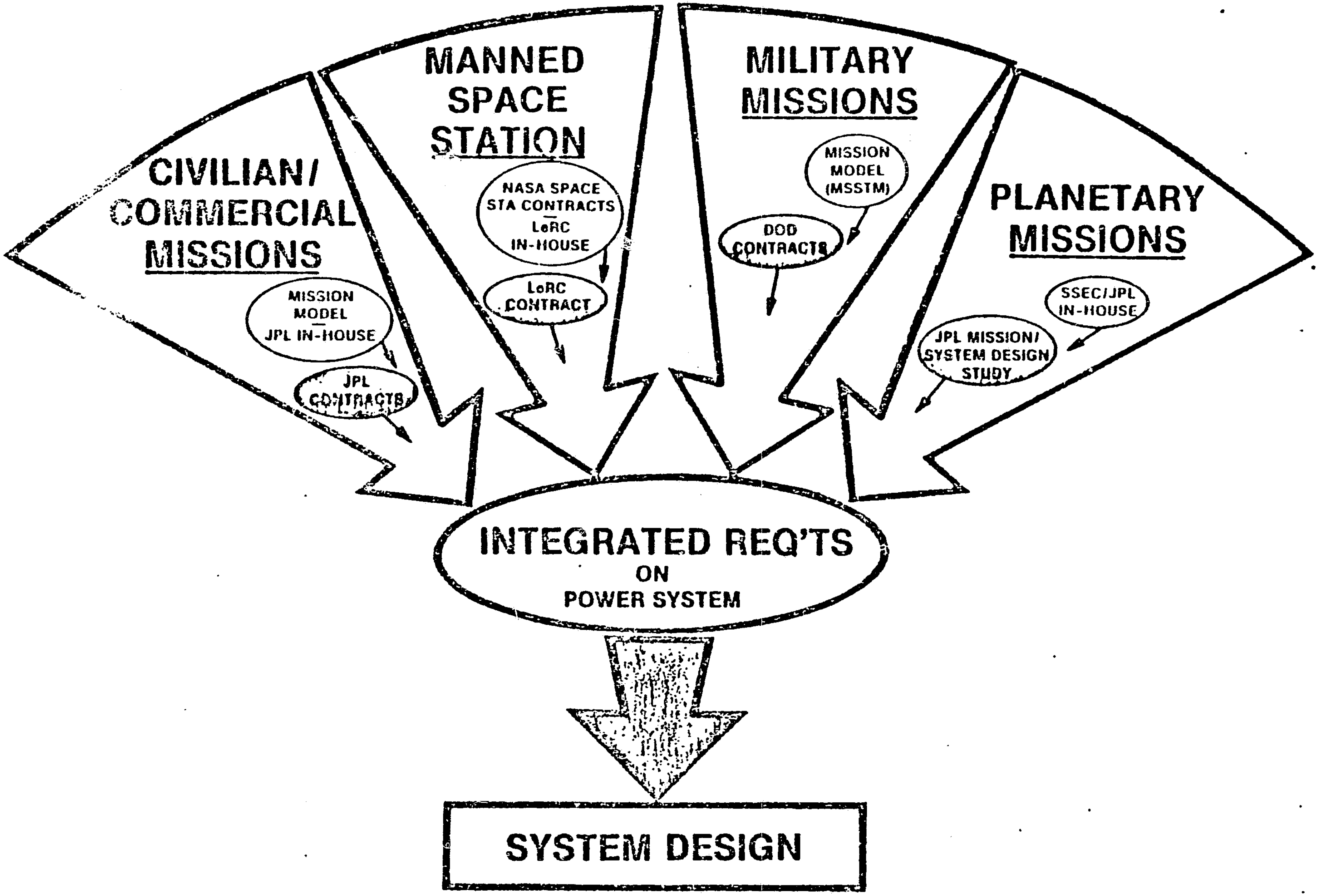

Fig. 3. SP-100 Mission Analysis and Requirements.

agencies will help generate mission requirements (Table 3) for the wide range of possible missions. The idea is to get a set of integrated requirements that can be applied in the development of an appropriate system. We would like to develop a concept that meets the needs of a multitude of missions. That may or may not be feasible. We may have such significantly different requirements -- between military and commercial applications, for example -- that a single power plant design may not be possible. To the extent it is possible, however, that is our goal. Organizationally, the work is divided along these lines. The Mission Analysis and Requirements area is headed up out of JPL. The Air Force and Navy are supplied monies to conduct military mission activities. JPL, NASA-LeRC, and various contractors are funded to do work in planetary, space station, and civil areas (Fig. 4).

To achieve the goals of the second major area, System Definition, we put out a request for bid the last part of 1982. We selected three system contractors: GA Technologies teamed with Martin Marietta Corporation, General Electric, and Westinghouse teamed with Lockheed. They are right now going through the initial screening of the various technologies. As a result of this work, there will be three formal reviews (Fig. 5). The first one occurred in June; the next one will be in September; and the final one, in December. Hopefully, we will select a contractor or contractors with one or more concepts sometime in February.

Basically what we asked the contractors to do was review a large array of possible technologies, with a number of constraints, the most important being that the power plant weigh less than 3,000 kg, produce at least 100 kW of power, and fit into no more than one-third of the shuttle bay. We are finding that meeting those constraints is by no means an easy task.

Table 3. Summary of mission requirement inputs to power system design

- Power use profile
- Mission survivability
- Mission duration/lifetime
- Start-up/load following/shut-off
- Dormancy
- Attitude control
- Launch vehicle compatibility (mass and size)
- Deployment
- Interfaces (power/mechanical/control/data)
- Environment (radiation, thermal, emi)
- Safety and cost implications

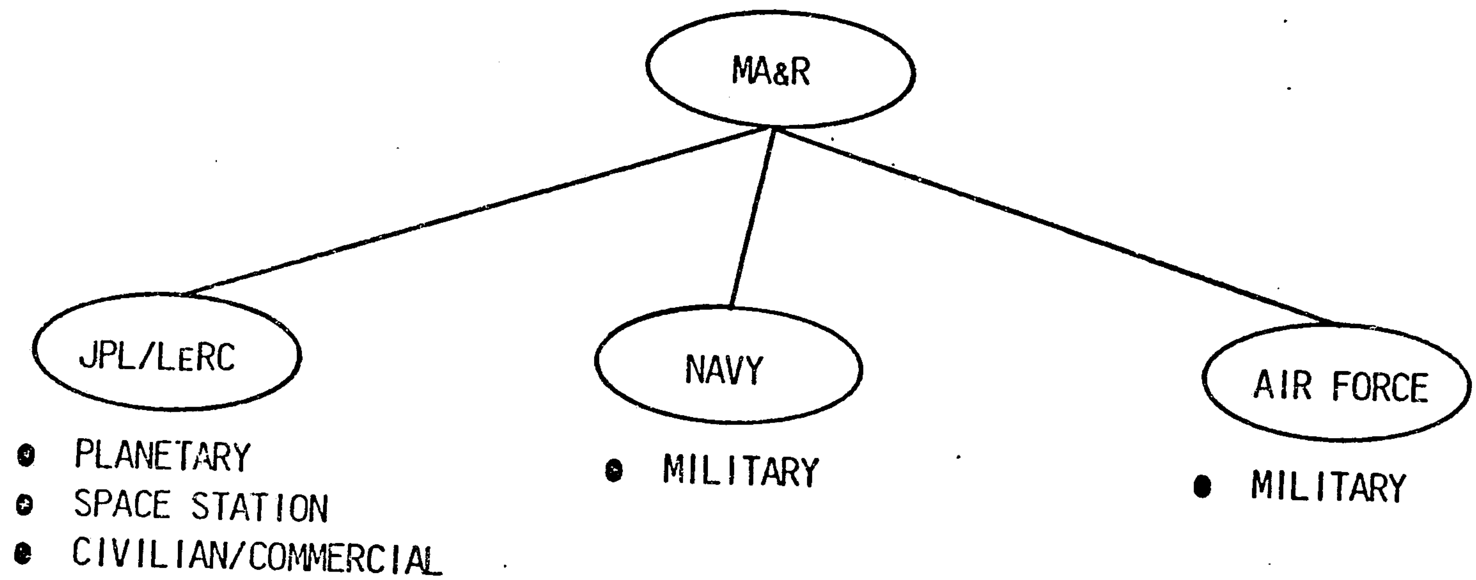

Fig. 4. Organizational support in the area of Mission Analysis and Requirements.

Table 4. Example missions considered with SP-100 power system

• Saturn ring rendezvous
• Jupiter satellite tour
• Uranus orbiter
• Neptune orbiter
• SP-100 class
• Advanced four-year mission

Table 5. Benefits of a nuclear power source for outer planet exploration

- Long-life, high-reliability power source
- Constant availability of high power
- Solar-independence
- Flexible use of low-thrust propulsion
  - High-mass payloads
  - Fast flight times
  - Flexible encounter capability (ring rendezvous, retrograde orbits, etc.)

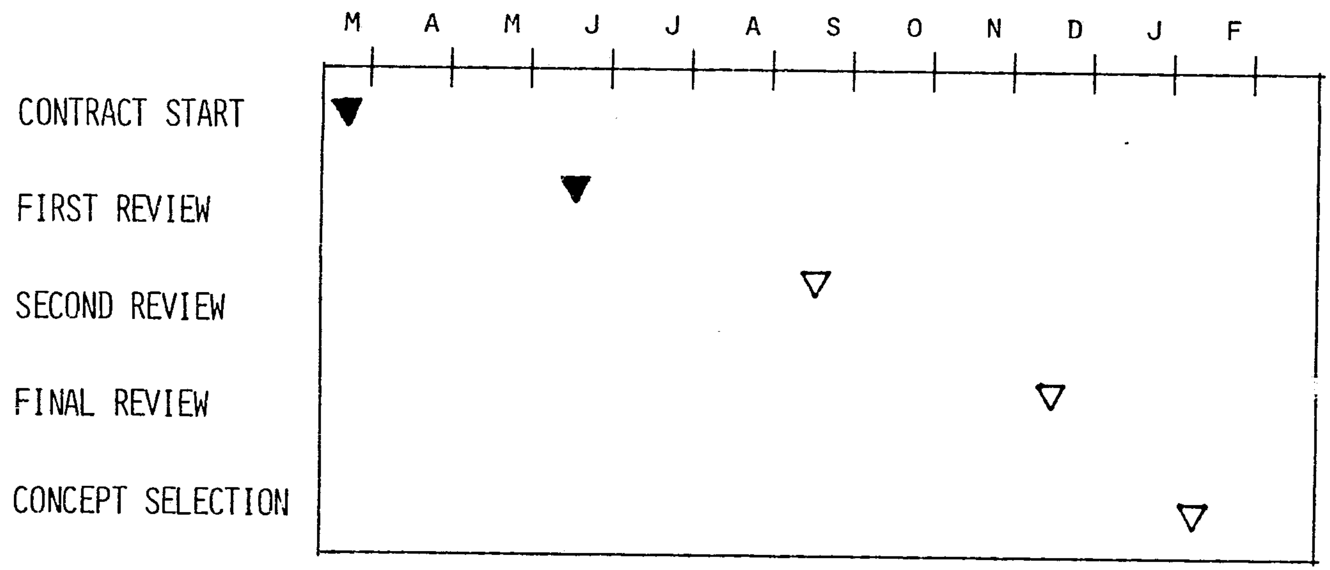

Fig. 5. Systems concept selection schedule.

We have a large number of options with respect to producing the electrical power from the thermal energy of the reactor. Figure 6 shows a hypothetical structural design of a concept using a dynamic heat engine. The reactor constitutes only a very small part of the volume, and even the weight, of the entire power system. What takes up most of the volume is the device that rejects the portion of power not converted into electricity — the waste heat radiator. This turns out to be quite a limiting aspect for the various design concepts being evolved. Our hope was to design a static radiator, which would not have to be deployed once placed in space. To meet the requirements of power and weight, however, it appears that many, though not all, of these concepts will have to use a deployable radiator.

The contractors have narrowed down the list of various technologies being considered (Table 6). For instance, they initially looked at thermal, epithermal, and fast reactors but, because of weight limitations, quickly zeroed in on a fast reactor. They have started looking at reactors cooled with gas, liquid-metal, and heat-pipe systems. As for power conversion devices, the program has the various dynamic conversion options of Brayton, Stirling, and Rankine cycles. For static conversion, there is thermoelectric; thermionic; in-core and out-of-core systems; and some new technologies (which are really in their infancy state but may well be good for growth versions), the alkali metal thermoelectric converter (AMTEC) and thermophotovoltaic conversion (TPV).

The system contractors are evaluating all of these options. In fact, they have narrowed down the list even further. Interestingly, each has a somewhat different view. Our job, therefore, is to come to grips with their several answers and to evaluate what does and does not make sense.

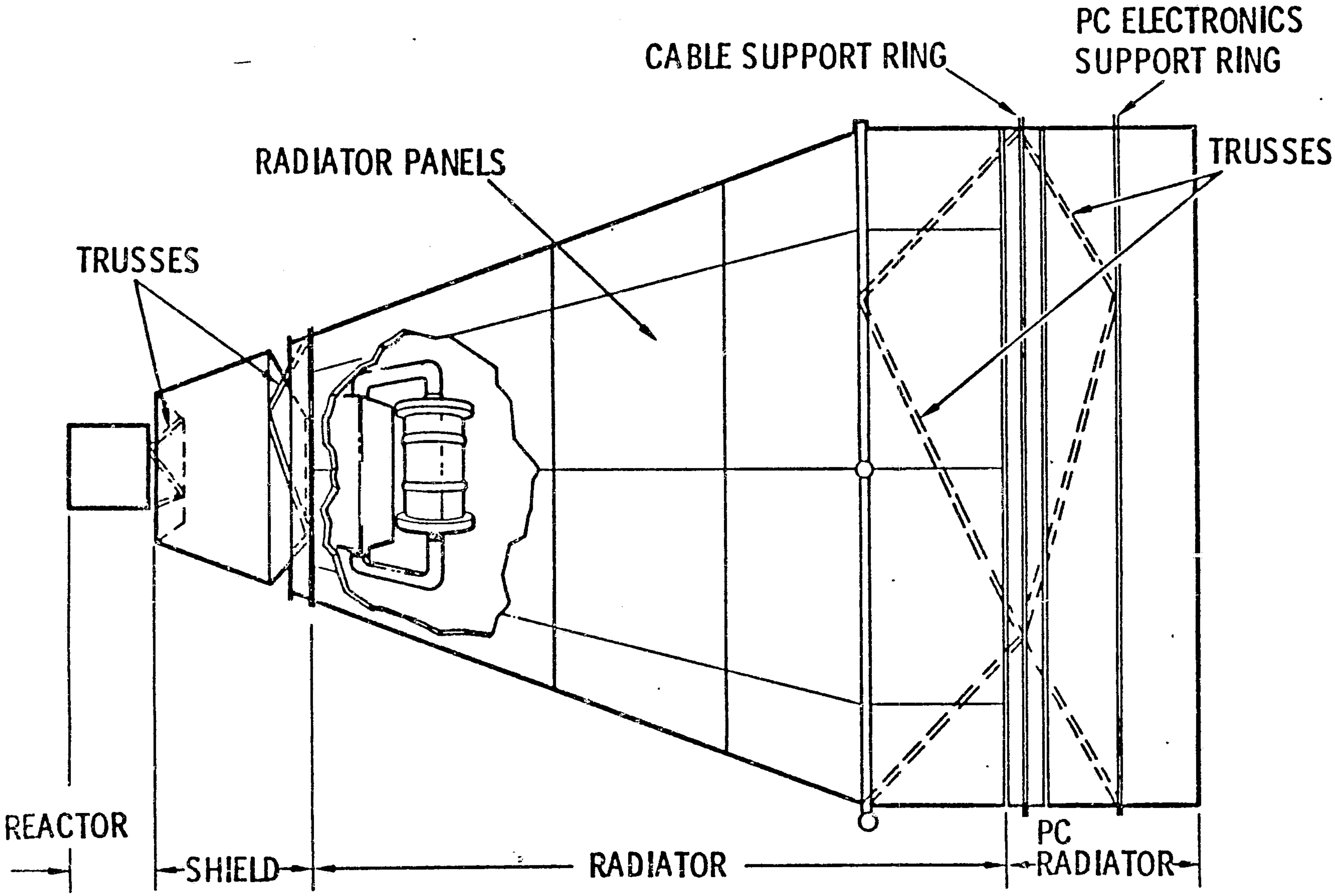

Fig. 6. SP-100 Aerospace Technology: hypothetical structural design of an SP-100 concept.

Table 6. Candidate subsystem concepts

Reactor	Power conversion
• Heat-pipe-cooled reactor (fast)	• Brayton
• Pumped liquid-metal-cooled reactor (fast)	• Stirling
• Gas-cooled reactor (fast)	• Rankine
	• Thermoelectric
	• Thermionic in-core
	• Thermionic out-of-core
	• AMTEC
	• TPV

To do that, we are trying to define what the technology program is going to be over the next two years. Here we run into problems: The sponsor needs an annual operating plan, and the Project Office needs a cost breakdown of exactly what is going to be done and why. The definitive inputs from the system contractors, however, are not due until December. So we have to make judgments as to what we ought to start doing right now. Using the significant data base that already exists at the various DOE laboratories and the NASA laboratories, such as JPL and NASA-LeRC, we set up a Technology Assessment Working Group (TAWG). In the last three or four months, this large team of government people have worked together to assess the options, identify which technologies make sense, and rank the options. This team has pretty much accomplished that task.

Although the system contractors have not agreed with one another, as a community the systems they selected do line up with those we evaluated independently and ranked at the top. The Project Office is comfortable with the direction that things are going right now. Whether we will be able to move ahead with all of these technologies or whether we have to downscope to an even smaller group, only the Program Office will tell.

In major areas 3 and 4, Aerospace and Nuclear Technology, the TAWG used the expertise of each laboratory. LANL, for example, examined the shield and reactor subsystems to determine where the technology is — what the reactor weighs per unit of power produced and what technical feasibility issues are associated with those subsystems. NASA-LeRC, with some support from ORNL, did the work on the dynamic machinery; and JPL did the work on the static subsystems.

REFRACTORY ALLOYS

Studies by JPL staff and a subset of the TAWG as well as inputs from the three systems design contractors reveal that to meet system requirements of a 3000-kg system weight and 100-kW output, use of refractory alloys is imperative. Why was this class of alloys identified? Clearly the leading candidates are those alloys that can operate at very high temperatures and have suitable creep strength (Fig. 7). For that reason we cannot live with super alloys — and certainly not with stainless steels, which are applicable at very low temperatures compared to the types of systems we are working on. A review of possible applications of the candidates tungsten-, molybdenum-, and tantalum-base alloys (Fig. 8) was conducted by the TAWG subset. As a result of this review, refractory alloy feasibility issues surfaced regarding core structural and fuel cladding applications in the nuclear subsystem as well as piping, heat exchanger, pump, turbine wheel, and Stirling cycle piston applications in the power conversion subsystem.

The area of refractory alloys is important, not only for the reactor but also for the power conversion system. The Project Office had to make sure the SP-100 Program did not take off in all directions, developing materials suitable for each particular power conversion, heat transport, and nuclear reactor application. To meet that challenge, we set up a structure that meets the needs of all these diverse applications (Fig. 9). The key is a technical planning team that defines materials needs. Made up of representatives from each of the major contributing laboratories, this team will define the requirements, the material development needs, and the

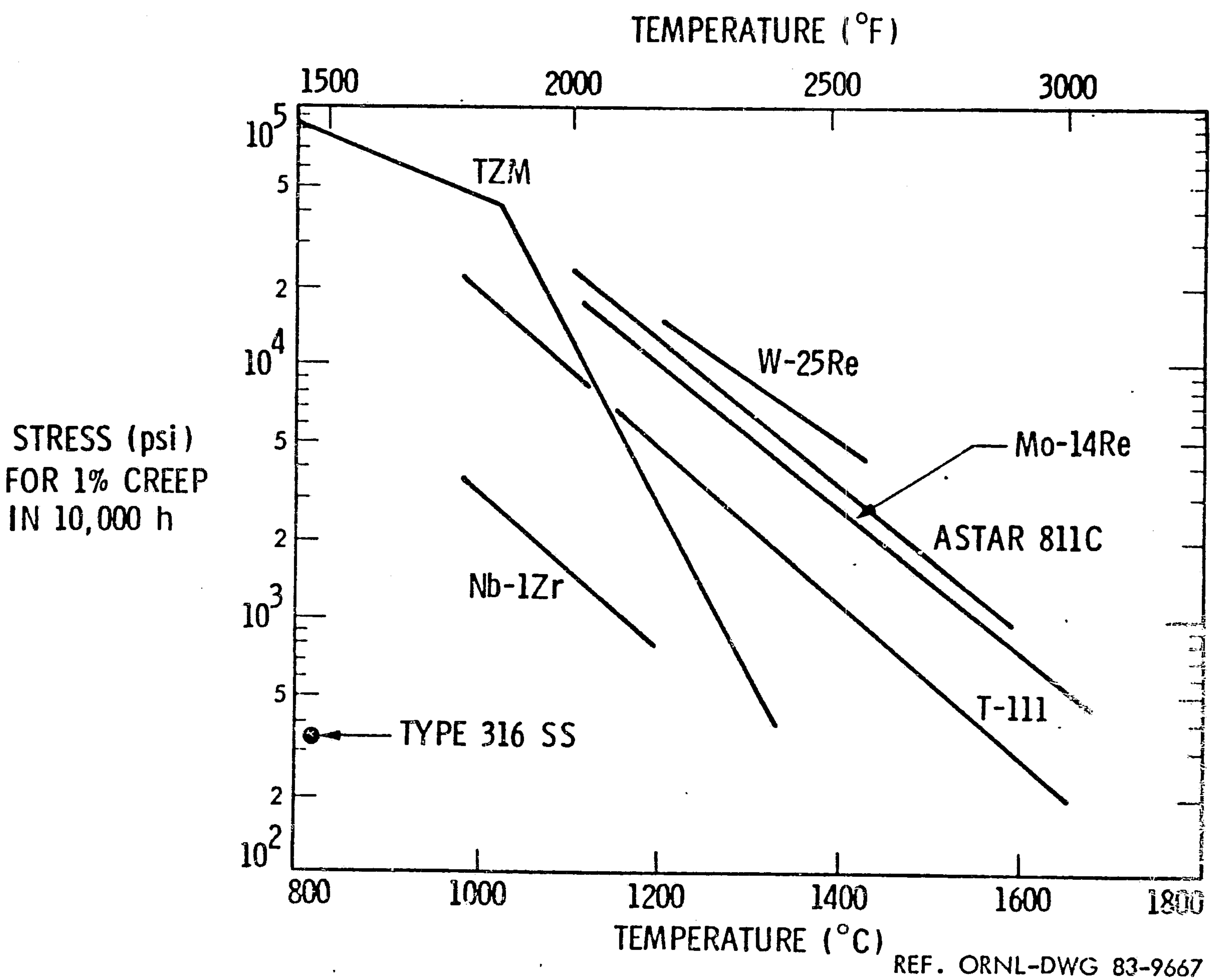

Fig. 7. SP-100 Aerospace Technology: high-temperature strength information for candidate alloys.

Major Application by Subsystem \ Candidate Alloy	W	MoRe	T-111	ASTAR 811C	TZM/TZC
NUCLEAR SUBSYSTEM Clad	Yes[a]	Yes	NA[b]	Yes[c]	NA
Core Structure (weldable)	NA	Yes	Yes	Yes	NA
POWER CONVERSION SUBSYSTEM Piping/HX Pumps	NA	NA	Yes	Yes	NA
Turbine Wheels/ Pistons	NA	Yes	NA	NA	Yes
Static Components	NA	NA	Yes	Yes	NA
Heat Pipes	NA	Yes	Yes	Yes	NA

[a]For in-core thermionic.
[b]NA—Alloy was not considered for this application.
[c]Used with tungsten liner.

Fig. 8. Possible application of candidate refractory alloys by major subsystem.

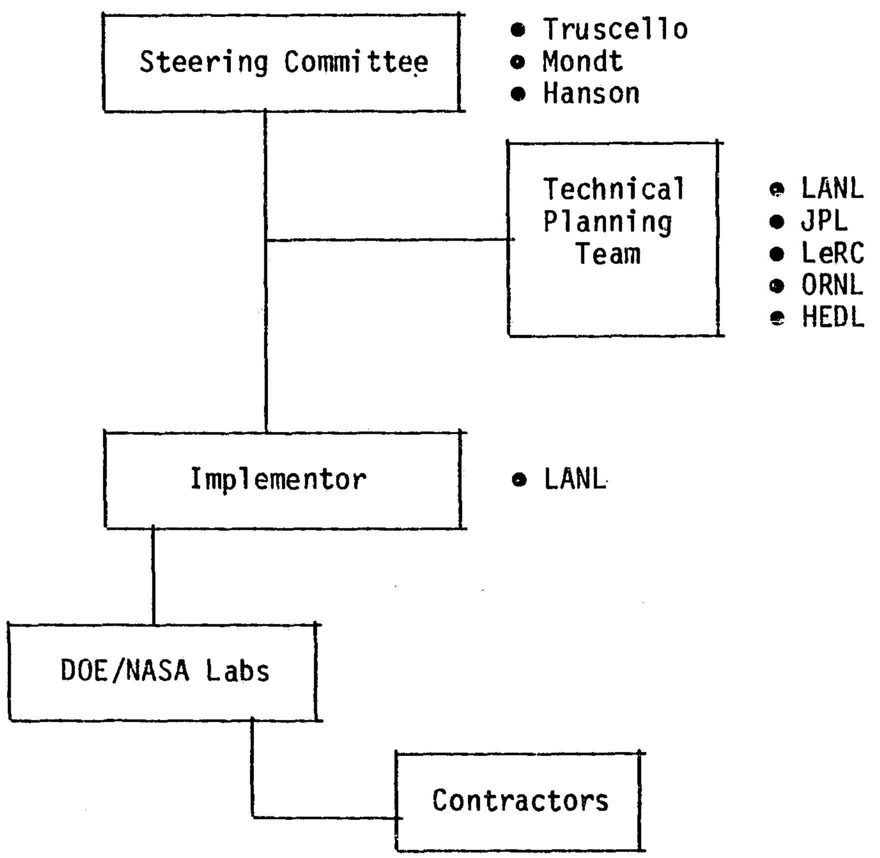

Fig. 9. Materials Development management structure.

costs and schedule to meet these needs. A steering committee made up of the Project Office and Aerospace and Nuclear Technology managers will act on the planning team's recommendations from a programmatic standpoint to determine (1) whether or not we can afford it, (2) how it fits in with all our other needs, and (3) when those particular needs are important and should be implemented. A group housed at LANL will lead the effort in implementing the actual development work through the various laboratories and contractors.

This planning team has identified a number of feasibility issues (Table 7) that have to be addressed between now and the end of the current phase of the program — which could be FY 1985. We have to understand chemical compatibility of the fuel, clad, and coolant; and we need a lot more data on such matters as irradiation behavior, specifically property degradation and swelling. Because the systems will not be operated during launch, we must ensure that materials do not fracture. Their toughness at low temperatures is critical. Another major concern is the potential degradation in performance by refractory metals as a result of contamination by oxygen, carbon, or nitrogen. These contaminants could be picked up from the fuel or by a fluid flowing through hot regions and deposited in colder ones. Use of inert gases as a working and transport fluid ought to solve the problem, but it does not. Because inert gases do not react with these impurities, they can transport them from one area to another, causing a buildup — and resulting in potential long-term failure of the components. Lithium, on the other hand, would be better, because it is a sink for most of these impurities. We need to do enough work on all these issues that

Table 7. Feasibility issues

CLAD	**PIPING/HX/PUMPS / HEAT PIPES**
(1) Chemical compatibility: fuel/clad/coolant	(1) Fracture toughness
(2) Irradiation behavior (swelling, property degradation)	(2) Mechanical properties
(3) Fracture toughness/crack growth rate	(3) Thick section weld
(4) Barrier integrity	(4) Very large diam pipe (3–4")
(5) Mechanical properties	(5) Inert gas compatibility
(6) Inert gas compatibility	(6) Life testing
CORE STRUCTURE	**TURBINE BLADES/PISTONS**
(1) Irradiation behavior	(1) High-temperature creep
(2) Fracture toughness	(2) Fatigue
(3) Mechanical properties	(3) Fabricability of wheel/ piston
(4) Thick section weld	(4) Inert gas compatibility
(5) Inert gas compatibility	

once we select a specific material combination and start moving ahead in engineering development, we will not run into any concerns that would force termination of the effort.

In summary, we are convinced that refractory alloys will be necessary to meet the needs of the power systems, whether they are used as fuel cladding, piping, heat pipes, turbines, or pistons. Tantalum- and molybdenum-based alloys are prime candidates to meet temperature and weight constraints. They may also be suitable for the fuel cladding, though tantalum alloys will require a barrier to the fuel. Tungsten-rhenium alloys are an alternative for fuel cladding. For selected power conversion system applications, tantalum- and molybdenum-based alloys again seem to be the best candidates. At these high temperatures, molybdenum-TZM is an extremely good candidate for turbine wheels for either a Brayton or a Rankine system. Both the tantalum and molybdenum alloys could be used for the heat pipes. Weldability concerns, on the other hand, mean molybdenum alloys may be less suitable for the reactor structure. We need to ascertain how weldable the molybdenum alloys are going to be and how much work is going to be necessary to prove they can be used for piping throughout the system or for the reactor structure. Clearly we must understand refractory metals.

SUMMARY

The SP-100 Program is expected to go through three phases: technology assessment and advancement, ground testing, and flight qualification. Currently the program is in the two- to three-year technology assessment and advancement stage, whose goals are to identify the space nuclear power system concept that best meets anticipated requirements of future space missions, assess the technical feasibility of that concept, and establish a cost and schedule for developing the concept. The SP-100 Project Office has begun the implementation activities needed to meet these goals, and we feel comfortable with the direction that things are going now. With regard to refractory alloys, we feel a better data base will be required before we move ahead in the program from technology assessment to ground demonstration.

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