NAA-SR-9213
SUPPLEMENT

1000-Mwe SGR AND PROTOTYPE EVALUATION STUDY

(SUPPLEMENT
JULY 1964)

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

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P.O. BOX 309 CANOGA PARK, CALIFORNIA

CONTRACT: AT(11-1)-GEN-8

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I. INTRODUCTION AND SUMMARY

This document is a supplement to NAA-SR-9213, "1000-Mwe SGR and Prototype Evaluation Study" which described the general design features, economics, and development of a large SGR plant. The economic analysis in the previous study was based on the first large advanced plant of this type. The reactor design and performance were based on currently available materials technology.

This supplement extends the previous work to show the reduction in capital costs which will result from experience gained in construction of a family of plants that are built in fairly prompt succession. Direct construction cost reductions in the reactor plant equipment are expected after the first or second plant, through redesign, simplification, and fabrication experience. In addition to lower capital costs, improvements in fuel cycle economics are expected through greater use of zirconium alloys. Both uranium and thorium fuel cycles are evaluated. The thorium design exploits the capability of the SGR to use alternate fuels.

The results of this additional analysis indicate that cost reductions from the first plant are readily possible, resulting in a total capital cost of $127,496,000 or $125/net kwe for an investor owned utility and $123,366,000 or $121/net kwe for a municipally owned utility. This includes direct and indirect plant costs, costs for land and rights, and interest during construction.

The power generation costs and fuel cycle costs under the present government fuel ownership conditions and under future private ownership conditions are given in Table 1. Case I is zirconium alloy clad UC with a stainless steel process tube; Case II is zirconium alloy clad UC with a zirconium alloy process tube; Case III is zirconium alloy clad UO_2-ThO_2 with a zirconium alloy process tube. In all cases the fuel rod is vented to avoid internal pressure buildup and permit the use of zirconium alloys at operating temperature.

These studies indicate that there is considerable incentive to develop zirconium alloys for high temperature sodium service and that ThO_2-UO_2 fuel can be used in the SGR as an economically attractive alternate to UC.

TABLE 1

SGR POWER GENERATION COSTS

UNIT COST (mills/kwh)

Unit	Case I UC/Zr/SS		Case II UC/Zr/Zr		Case III UO_2-ThO_2/Zr/Zr	
	Present Government Ownership	Future Private Ownership	Present Government Ownership	Future Private Ownership	Present Government Ownership	Future Private Ownership
Fuel cycle cost	1.23	1.04	1.13	0.92	0.93	0.93
Operating cost	0.20	0.20	0.20	0.20	0.20	0.20
Fixed cost	2.73	2.71	2.72	2.70	2.70	2.69
Total power generation cost	4.16	3.95	4.05	3.82	3.83	3.82

II. SUPPLEMENTARY REACTOR DESIGN BASES

Three reactor designs are considered in this evaluation. These designs represent technical improvements over the design described in NAA-SR-9213, Volume I. The technical accomplishments required to realize these improvements are believed to be attainable by 1970. Selected design and operating parameters are shown in Table 2. The process operating conditions are identical to those described in NAA-SR-9213.

The first design, Case I, uses uranium carbide fuel clad in zirconium alloy tubes with a sodium bond; the fuel rods vent fission gases directly to the reactor atmosphere. Because of the venting feature, employment of zirconium-base material at 1250°F is considered feasible. Based on preliminary experimental evidence developed at Atomics International and other installations (Reference Canadian Report from AECL, FD-34-18 April 1964, and, Armour Research Report ARF-2234-7 September 1962), zirconium alloys, both wrought and dispersion-strengthened types, have satisfactory properties for cladding-applications to at least 1250°F in sodium cooled reactors. Experimental work shows the material to be compatible with UC fuel and sodium. Carburization of these materials by hyperstoichiometric UC results in the formation of a thin carbide diffusion barrier on the cladding surface. Diffusion of carbon through the carbide layer is the rate-controlling process. Unlike the carburization of stainless steel by hyperstoichiometric UC, carburization of Zr alloy is independent of fuel temperature and fuel carbon content, depending only on the cladding temperature. (Reference NAA-SR-7502, Compatibility of UC with Clad Materials, P. Elkins and Irradiation Behavior of UC Fuels, Sinizer, et al.) Diffusion rates are extremely slow at cladding temperatures below 1250°F.

The remarks above regarding the carburization of zirconium alloy cladding also apply to a zirconium process tube; however, the source of carbon would be the sodium. Hot traps provided in the plant design will maintain the carbon within acceptable limits.

A knowledge of physical and mechanical properties of Zr is required for optimum fuel rod design. The strength characteristics of the alloys are adequate at 1250°F, in the vented fuel rod design, since no internal fission gas pressure buildup occurs.

TABLE 2

DESIGN AND OPERATING PARAMETERS FOR AN EARLY 1000-Mwe SGR NUCLEAR POWER PLANT

TABLE 2

DESIGN AND OPERATING PARAMETERS FOR AN EARLY 1000-Mwe SGR NUCLEAR POWER PLANT

Parameter	NAA-SR-9213 Volume I	Case I	Case II	Case III
Reactor Core				
Plant net electrical output (Mwe)	1,019	1,019	1,019	1,019
Reactor thermal power (Mwt)	2,336	2,336	2,336	2,336
Fuel Material	UC	UC	UC	ThO_2-UO_2
Active Core Size dia x height (ft)	25.1 x 14	25.4 x 14	23.6 x 14	23.6 x 14
Fuel elements in core	595	594	512	512
Core inventory (kg of U or U + Th)	73,800	73,700	64,500	38,500
Control Elements	84	102	88	88
Average core specific power (kw/kg of U or U + Th)	31.7	31.2	36.2	60.7
Fuel Management Program	4 zone graded	6 zone graded		
Process tube material	SS	SS	Zr alloy	Zr alloy
Process tube thickness (in.)	0.025	0.025	0.050	0.050
Process tube OD (in.)	4.00	4.00	4.00	4.00
Fuel				
Slug diameter (in.)	0.500	0.500	0.500	0.387
Clad thickness (in.)	0.010	0.020	0.020	0.020
Clad OD (in.)	0.570	0.580	0.580	0.432
Clad material	SS	Zr alloy	Zr alloy	Zr alloy
Clad thermal bond material	Na	Na	Na	Gas
Maximum hot channel fuel temperature (°F)	2,000	2,075	2,250	5,000
Maximum fuel rod linear power (kw/ft)	33.0	35.1	40.7	24.4

The vented fuel rod design considered in these concepts releases only the noble gas fission products, Xe and Kr, to the reactor atmosphere. The reactor plenum atmosphere must be continually circulated through activated charcoal traps to reduce the ambient level of these gases to acceptable limits. Periodically, the gas stored on the charcoal is transferred to storage tanks for decay and ultimate controlled release. The vented fuel element concept has been used successfully in the Dounreay fast reactor fuel elements to burnups of 1.5 atom%. The Dounreay element is a fully vented element in which the bond sodium is completely free to interchange with the coolant. This concept allows all of the fission products to be transported throughout the system. The January 1964 issue of Nuclear Engineering completely describes the latest developments in Dounreay fuel technology. The vented elements have operated successfully without causing serious plant operation or maintenance problems. It should be noted that the LSGR vented fuel design is conservative in that the initial concept is for venting of the fission gases only.

Case II is essentially the same as Case I, except that the stainless steel process tube is replaced with a zirconium alloy tube. Since the basic calandria vessel which includes the shell and upper and lower grid plates would still be fabricated from stainless steel for economy reasons, a transition joint would be required for the zirconium process tubes.

Preliminary experiments conducted at Atomics International have indicated the compatibility of zirconium-iron diffusion couples at 1000, 1100, 1200, 1400, and 1600°F to 2000 hours. Significant metallurgical reactions do not occur below 1200°F. Mechanical property tests have substantiated this conclusion. No significant increase in the hardness at the dissimilar metal interface, or decrease in the shear strength of the joint was noted when the exposure temperature was maintained below 1200°F. Some reactions were noted when the exposure temperature was greater than 1400°F. This study also evaluated various materials (tantalum, columbium, and vanadium) for use as diffusion barriers at the Zr-Fe interface. Barriers may be required if the selected joining process uses temperatures above the eutectic melting temperature of the combination. Commercial suppliers of zirconium-stainless steel transition joints do not anticipate serious problems in supplying such transitions of the size or for the operating conditions required.

Case III is a Th-U cycle using mixed oxide fuel, ThO_2-UO_2. The fuel rods use zirconium alloy cladding which is helium gas bonded and vented. Also, the zirconium alloy process tube is used in the calandria structure as in Case II. This design selection was made from a brief parametric study. However, the operating and burnup conditions are believed to be conservative, based on preliminary data. Recent work at ORNL has shown the high irradiation stability of the ThO_2-UO_2 fuel tested in capsule scale to greater than 60,000 Mwd/MT. Reactor operation with oxide fuels at or near the melting point of the oxide has also recently been demonstrated by General Electric; thus, the use of 5000°F peak central fuel temperature is a reasonable design value.

III. ECONOMICS

A. SUMMARY

Power generation costs are based on AEC evaluation ground rules as specified in TID-7025, "Guide to Nuclear Power Cost Evaluation" and on an 80% annual plant factor and fixed charge rates representative of both investor-owned and municipally-owned utilities. The ground rules have been modified by using indirect costs based on experience at Atomics International, and fuel cycle cost data representing present government ownership and future private ownership.

Power costs for an early plant in a family of large SGR's are summarized in Table 3. These costs consider the decreases which will result from the experience in the design and construction of the first large SGR's. The plant construction cost is $114,746,000 or $113/kw and the fuel costs range between 0.92 and 1.23 mills/kwh depending on the fuel cycle and fuel ownership status. Escalation is not considered.

B. CAPITAL COSTS

The capital costs presented in Volume I of the parent report are based on the construction cost of the first large advanced sodium-graphite reactor. The costs presented in this supplement are based on a 1000-Mwe power station which is assumed to be an early member of a family of large SGR's rather than a single isolated plant. As a result of experience accumulated in the construction and operation of the SGR prototype and the first large SGR plants, reductions in direct and indirect construction costs will be realized. The cost reductions will be mainly in fabrication of reactor plant equipment and in engineering and design.

The total capital cost is $127,496,000 ($125/kw) for an investor-owned plant and $123,366,000 ($121/kw) for a municipally-owned plant. A summary of the total construction costs is given in Table 4. Details of the direct construction costs are tabulated, according to the preferred AEC accounting systems, in Table 5. Direct construction cost estimates are based on vendor quotes for major equipment items as established in Volume I, with a reduction of approximately 10% in the reactor equipment accounts (Account 22). Direct construction cost reductions in this area are reasonable to expect through redesign, simplification, and fabrication experience.

TABLE 3

ENERGY COST FOR AN EARLY 1000-Mwe SGR NUCLEAR POWER PLANT (mills/kwhr)

Unit	Case I		Case II		Case III	
	Present Gov't. Ownership	Future Private Ownership	Present Gov't. Ownership	Future Private Ownership	Present Gov't. Ownership	Future Private Ownership
FIXED CHARGES						
Depreciating capital (14.5%)	2.59	2.59	2.59	2.59	2.59	2.59
Total capital cost (less land and land rights						
Nondepreciating capital						
Land and land rights (13%)	0.01	0.01	0.01	0.01	0.01	0.01
Working capital (13%)						
a) Plant operation and maintenance	0.01	0.01	0.01	0.01	0.01	0.01
b) Fuel cycle operations	0.07	0.05	0.06	0.04	0.04	0.03
Nuclear liability insurance	0.05	0.05	0.05	0.05	0.05	0.05
Subtotal, annual fixed charges	2.73	2.71	2.72	2.70	2.70	2.69
OPERATING COSTS						
Fuel cycle cost	1.23	1.04	1.13	0.92	0.93	0.93
Operating and maintenance cost	0.20	0.20	0.20	0.20	0.20	0.20
Subtotal - operating cost	1.43	1.24	1.33	1.12	1.13	1.13
Total power generation cost	4.16	3.95	4.05	3.82	3.83	3.82

TABLE 4

SUMMARY OF CONSTRUCTION COST ESTIMATE FOR AN EARLY 1000-Mwe SGR NUCLEAR POWER PLANT

Acc't. No.	Unit Description	$ in 000 Material & Equipment	Labor	Total
Direct construction cost				
21	Structures and improvements	5,534	4,562	10,096
22	Reactor plant equipment	40,598	9,498	50,096
23	Turbine generator equipment	22,054	2,543	24,597
24	Accessory electric equipment	1,753	947	2,700
25	Misc. power plant equipment	657	200	857
	Total	70,596	17,750	88,346
Indirect construction costs				
General and administrative				6,500
	Subtotal			94,846
Misc. construction				700
	Subtotal			95,546
Engineering, design and inspection services				6,000
	Subtotal			101,546
Startup				1,200
	Subtotal			102,746
Sodium and gases (initial charge)				560
	Subtotal			103,306
Contingency				11,440
Base Plant Cost				114,746
Base Cost per net kw (plant net output - 1,019,100 kw) = $113				

Total Evaluated Cost, Investor-Owned	
Land and land rights	360
Interest during construction (48 month schedule - 10.8%)	12,390
	127,496
Total Cost per net kw (plant net output - 1,019,100 kw) = $125	
Total Evaluated Cost, Municipally-owned	
Land and land rights	360
Interest during construction (48 month schedule - 7.2%)	8,260
	123,366
Total Cost per net kw (plant net output - 1,019,100 kw) = $121.	

TABLE 5

DETAILS OF DIRECT CONSTRUCTION COST ESTIMATE FOR AN EARLY 1000-Mwe SGR NUCLEAR POWER PLANT

Account Number	Description	$ in 000 Material	Labor	Total
20	Land and land rights			
201	Land and privilege acquisition			360
202	Relocate highway and railroads			
203	Relocate phone and power lines			
	Total acc't 20			360
21	Structures and improvements			
211	Ground improvements			
.1	Access roads (off-site)			
.2	General yard improvements			
.21	Grading and landscaping	180	120	300
.22	Roads, sidewalks, and parking areas	60	30	90
.23	Retaining walls, fences and railings	90	75	165
.24	Outside water dist. systems	60	40	100
.25	Sewers and drainage systems	120	80	200
.26	Roadway and general lighting	10	6	16
	Subtotal acc't 211.2	520	351	871
.3	Railroad 5 mi	200	100	300
.4	Waterfront improvements	200	100	300
	Subtotal acc't 211	920	551	1,471
212-A	Turbine-generator bldg.			
.1 and .2	Excavation and backfill	70	75	145
.3	Substructure	300	360	690
.4	Superstructure	470	290	760
.6	Building services	210	155	365
	Subtotal acc't 212-A	1,080	880	1,960
212-B	R/A waste bldg.			
.1	Excavation and backfill	3	9	12
.3	Substructure	65	75	140
.6	Building services	13	10	23
	Subtotal acc't 212-B	81	94	175
212-C	Administration bldg.			
.1	Excavation and backfill	7	28	35
.3	Substructure	47	28	75
.4	Superstructure	103	84	187
.6	Building services	47	30	77
	Subtotal acc't 212-C	204	170	374

TABLE 5 (Cont'd)

DETAILS OF DIRECT CONSTRUCTION COST ESTIMATE FOR AN EARLY 1000-Mwe SGR NUCLEAR POWER PLANT

Account Number	Description	$ in 000 Material	Labor	Total
212-D	Reactor building w/aux. bay and steam generator bldg			
.1	Excavation and backfill	73	273	346
.3	Substructure	1,500	1,458	2,958
.4	Superstructure	950	607	1,557
.6	Building services	600	450	1,050
	Subtotal acc't 212-D	3,123	2,788	5,911
212-E	Warehouse			
.1	Excavation and backfill	2	10	12
.3	Substructure	8	4	12
.4	Superstructure	24	16	40
.6	Building service	10	6	16
	Subtotal acc't 212-E	44	36	80
212-F	Gate house	12	8	20
212-G	Misc. outdoor foundations	10	15	25
218	Stack	60	20	80
	Total acc't 21	5,534	4,562	10,096
22	Reactor plant equipment			
221	Reactor equipment			
.1	Reactor vessel w/internals	453	1,300	2,253
.2	Reactor controls	3,523	30	3,553
.3	Reactor shielding	1,360	220	1,580
.4	Reactor cool. and heat systems	1,700	800	2,500
.5	Reactor plant containers	650	750	1,400
.6	Calandria moderators and reflectors	2,600	500	3,100
.7	Reactor plant cranes and hoists	203	12	215
	Subtotal acc't 221	10,989	3,612	14,601
222	Heat transfer systems			
.1	Reactor primary coolant system	1,950	300	2,250
.2	Intermediate coolant system	6,110	390	6,500
.3	Stm. gen. S.H. and R.H. system	8,510	1,400	9,910
.4	Reactor cool. rec. sup. and treatment	1,523	400	1,023
	Subtotal acc't 222	18,093	2,490	20,583

TABLE 5 (Cont'd)

DETAILS OF DIRECT CONSTRUCTION COST ESTIMATE FOR AN EARLY 1000-Mwe SGR NUCLEAR POWER PLANT

Account Number	Description	$ in 000 Material	Labor	Total
223	Fuel, C.R. and mod. hdlg. and storage equip.			
.1	Cranes and hoist equipment	725	30	755
.2	Special tools and services	250	0	250
.3	Storage cool. clean. and insp. serv.	720	200	920
	Subtotal acc't 223	1,695	230	1,925
225	R/A waste-treated disposal			
.1	Liq. waste system	125	45	170
.2	Gaseous waste system	120	60	180
	Subtotal acc't 225	245	105	350
226	Inst. and control			
.1	Contr. rm. console and panels	1,070	330	1,400
.2	Locally mtd. instr.	2,260	440	2,700
.3	H.P. instr.	70	0	0
.4	Control valves	890	in piping	890
.5	Connect. and supports	231	350	581
	Subtotal acc't 226	4,521	1,120	5,641
227	Feedwater sup. and treat.	2,790	590	3,380
228	Stm. cond. and feedwater sys.	1,810	1,196	3,006
229	Other reactor plant equip.			
.1	Equip. decontam. system	140	70	210
.2	React. plant maint. system	315	85	400
	Subtotal acc't 229	455	155	610
	Total acc't 22	40,598	9,498	50,096
23	Turbine generating plant equip.			
231	Turbine generators			
.1	Foundations-pedestal	151	185	336
.2	Turbine-generator	17,767	780	18,547
.3	Standby exciter	517	30	547
	Subtotal acc't 231	18,435	995	19,430
232	Circulating water system			
.1	Pumping and regulating equip.	670	53	723
.2	Circulating water lines	434	197	631
.3	Intake and discharge structures	552	342	894
.4	Corrosion cont. and water treat. sys.	34	6	40
	Subtotal acc't 232	1,690	598	2,288

TABLE 5 (Cont'd)

DETAILS OF DIRECT CONSTRUCTION COST ESTIMATE FOR AN EARLY 1000-Mwe SGR NUCLEAR POWER PLANT

Account Number	Description	$ in 000 Material	Labor	Total
233	Condensers and auxiliaries	1,000	340	1,340
234	Central lube sys.	37	23	60
235	Turbine plant instr. and control	360	340	700
236	Turbine plant piping	500	213	713
237	Auxiliary equip. for generators	32	34	66
	Total acc't 23	22,054	2,543	24,597
24	Accessory electric equipment			
241	Switch gear	750	223	973
242	Switch boards			
.1	Main control board	55	11	66
.2	Aux. power, battery and signal bds.	68	11	79
.3	Motor control centers	84	16	100
	Subtotal acc't 242	207	38	245
243	Protective equipment	18	34	52
244	Electrical structures	26	92	118
245	Conduit	60	229	289
246	Power and control wiring	140	255	395
247	Station service equipment	552	76	628
	Total acc't 24	1,753	947	2,700
25	Misc. power plant equip.			
251	Crane and hoisting equipment	365	35	400
252	Compressed air and vacuum clean. sys.	125	70	195
253	Other power plant equip.	167	95	262
	Total acc't 25	657	200	857

Indirect construction costs, which were added to the total direct construction estimate of $88,346,000 include: administrative costs; miscellaneous construction, engineering, design and inspection; costs and costs for startup, sodium and gases, and contingencies. These costs are anticipated to be significantly lower than those for the preceding plants. Engineering and design costs will be reduced due to standardization of component drawings, specifications, procedures and special reports, and analysis. Cost reductions in other administration and technical areas are also possible. The indirect cost estimates shown in Table 4 are based on experience at Atomics International and do not necessarily agree with the standard AEC ground rules commonly used for preliminary evaluations.

The estimated total base plant cost to a utility, excluding normal customer cost for land and land rights and interest during construction, is $114,746,000 or $113/kw, based on a net plant output of 1,019,000 kw. Land and land rights are estimated at $360,000. Interest during construction is based on a construction period of 48 months and the assumed expenditure curve contained in the AEC Guide. The construction interest charge for the plant depends on the type of utility ownership. The annual interest rate applicable to investor owned and municipally owned utilities was assumed to be 6 and 4%, respectively.

C. FUEL CYCLE COSTS

One of the attractive features of the SGR concept is its ability to use different fuels to good advantage. Studies of several advanced fuel cycles which are likely to provide improved fuel cycle costs for the SGR have recently been completed. Three basic cases which represent improvements over the reference fuel of Volume I are presented in this supplement. In this brief study the reactor has not been optimized for each fuel separately. It is reasonable to expect that one or all of these cycles will be available for incorporation in the SGR in the early 1970's. Fuel cycle date for these cases are shown in Table 6.

The higher lease charge which is expected to prevail in a private ownership economy will change the fuel burnup level at which fuel cycle costs are a minimum. Under the government ownership cases using a 4-3/4% lease charge, the fuel cycle cost for UC fuel is still decreasing with increased burnup at 35,000 Mwd/MTU; but, in the private ownership cases using a 10% lease charge, the minimum fuel cycle cost occurs between 25,000 and 35,000 Mwd/MTU, being practically the same over this range. Thus, with higher lease charge rates, very high burnups may not be economically justified. For the UC cases (Case I and II) of this study, an average burnup of 35,000 Mwd/MTU was used for government ownership of uranium; an average burnup of 25,000 Mwd/MTU was used for private ownership. The ThO_2-UO_2 cycle was evaluated at 60,000 Mwd/MTU+Th average; the most economical burnup level for this case has not been determined.

TABLE 6

FUEL CYCLE DATA FOR AN EARLY
1000-Mwe SGR NUCLEAR POWER PLANT

	Present Government Ownership	Future Private Ownership
Economic Data		
Plant capacity factor (%)	80	
Preirradiation fuel inventory time (Mo)	6	
Postirradiation fuel inventory time (Mo)	6	
Size of reprocessing batch	1/6 of core	
Reprocessing plant daily rate (tons)	AEC schedule	5
Reprocessing plant daily cost ($)	18,000	$10/kg*
Reprocessing plant turn-around time (days)	8	
Fuel lease rate (%)	4-3/4	10
U_3O_8 price ($/lb)	8.00	5.00
ThO_2 price ($/lb)	5.00	5.00
Plutonium-239, 241 price ($/g)	10.00	8.60
Uranium-233 price	14/12 of uranium-235 price	
Separative work cost ($/kg)	30.00	30.00
UC fuel fabrication cost (incl. shipping) ($/kg U)	90.00	60.00
Th-U fuel fabrication cost (incl. shipping) ($/kg U + Th)	100.00	65.00

Nuclear Data	Case I		Case II		Case III	
	Present Government Ownership	Future Private Ownership	Present Government Ownership	Future Private Ownership	Present Government Ownership	Future Private Ownership
Average fuel exposure (Mwd/MTU or U + Th)	35,000	25,000	35,000	25,000	60,000	60,000
Uranium-235, initial (wt %)	4.00	3.09	3.50	2.70	6.18	6.18
Uranium-235, final (wt %)	1.14	1.06	0.82	0.79	1.75	1.75
Uranium-233, final (wt %)	---	---	---	---	1.77	1.77
Plutonium-239, 241, final (wt %)	0.417	0.367	0.369	0.342	---	---
Average in-core residence time at 80% (yr)	4.74	3.67	4.03	3.16	3.39	3.39

*ORNL-TM-678, "Partially Enriched Fuel Cycles," Floyd L. Culler Jr., September 3, 1963

The first design, Case I, is sodium-bonded uranium carbide fuel, clad in zirconium alloy, with fission gas venting directly to the reactor coolant. The fuel cycle costs for this case are given in Table 7. The first column of this table represents present-day uranium cost and government ownership conditions, the second column is generally representative of the costs that can be expected to prevail in the early 1970's under private ownership conditions.

TABLE 7

FUEL CYCLE COSTS FOR AN EARLY 1000-Mwe SGR NUCLEAR POWER PLANT, CASE I
(UC, Zr-Clad and Stainless-Steel Process Tube)

Unit ($/kg U)	Present Gov't. Ownership	Future Private Ownership
Fuel Depletion Costs		
Initial uranium value	365.80	216.22
Final uranium value	(57.37)	(37.94)
Final plutonium value	(41.70)	(32.34)
	266.73	145.94
Fabrication and Reprocessing Costs		
Fabrication	90.00	60.00
Irradiated fuel shipping	9.48	5.00
Reprocessing	30.12	10.00
Conversion	5.26	3.00
1.3% Uranium losses	0.74	0.50
	135.60	78.50
Fuel Inventory Charges		
4-3/4% lease on uranium	47.62	
10% lease on uranium and Pu		46.64
	47.62	46.64
Total	449.95	271.08
(mills/kwhr)	1.23	1.04

Case II is essentially the same as Case I, except the stainless steel process tube is replaced with a zirconium alloy tube. The fuel cycle costs are given in Table 8.

Case III is based on the Th-U cycle, using mixed oxide fuel, clad in zirconium alloy, using the zirconium alloy process tube as in Case II. The cost figures of Table 9 are based on an equilibrium once-through fuel cycle, and neglect any penalty for U-232, which would not exceed about 0.15 mills/kwhr.

TABLE 8

FUEL CYCLE COSTS FOR AN EARLY 1000-Mwe SGR NUCLEAR POWER PLANT, CASE II
(UC, Zr-Clad and Zr Process Tube)

Unit ($/kg U)	Present Gov't. Ownership	Future Private Ownership
Fuel Depletion Costs		
Initial uranium value	309.75	180.04
Final uranium value	(30.55)	(19.82)
Final plutonium value	(36.90)	(29.41)
	242.30	130.81
Fabrication and Reprocessing Costs		
Fabrication	90.00	60.00
Irradiated fuel shipping	9.49	5.00
Reprocessing	32.34	10.00
Conversion	5.26	3.00
1.3% uranium losses	.40	.25
	137.49	78.25
Fuel Inventory Charges		
4-3/4% lease on uranium	32.57	
10% lease on uranium and Pu		31.58
	32.57	31.58
Total	412.36	240.64
(mills/kwhr)	1.13	0.92

TABLE 9

FUEL CYCLE COSTS FOR AN EARLY 1000-Mwe SGR NUCLEAR POWER PLANT, CASE III
(ThO_2-UO_2, Zr Clad and Zr Process Tube)

Unit ($/kg U+Th)	Present Gov't. Ownership	Future Private Ownership
Fuel Depletion Costs		
Initial uranium-235 value	743.88	639.65
Initial Th value	11.69	11.69
Final uranium-235 value*	(199.39)	(171.08)
Final uranium-233 value*	(236.25)	(202.73)
	319.93	277.53
Fabrication and Reprocessing Costs		
Fabrication	100.00	65.00
Irradiated fuel shipping	10.00	5.00
Reprocessing	49.65	10.00
1% uranium losses	4.36	3.74
	164.01	83.74
Fuel Inventory Charges		
4-3/4% lease on U-235	98.34	
10% lease on U-235 and U-233		222.45
	98.34	222.45
Total	582.28	583.72
(mills/kwhr)	0.93	0.93

*No U-232 penalty applied.

The U-232 penalty announced recently by the AEC in the Federal Register is considerably larger than the expected increase of fabrication cost due to the remote refabrication of ThO_2-UO_2 fuel elements in a recycled fuel scheme. Since the fuel depletion costs in a recycled fuel management program are considerably lower than for a once-through cycle, neglecting the U-232 penalty would seem to set a conservative upper limit to the fuel costs of a thorium cycle in the Sodium Graphite Reactor.

D. OPERATION AND MAINTENANCE, NUCLEAR LIABILITY INSURANCE, AND WORKING CAPITAL COSTS

The costs of O&M, insurance, and working capital are not significantly affected by the changes in the fuel cycle. The derivation and details of these costs are given in Volume I and are summarized here for the sake of completeness. The estimated annual premium and fee for nuclear liability insurance is $330,000. Table 10 summarizes the O&M costs and Table 11 the working capital requirements.

TABLE 10

SUMMARY OF ANNUAL OPERATION AND MAINTENANCE COSTS ON 1000-Mwe SGR

Direct payroll costs	$ 468,800
Fringe benefits at 20%	93,800
Total Labor	562,600
Operating supplies and maintenance	864,400
	$1,427,000

TABLE 11

WORKING CAPITAL FOR 1000-Mwe SGR

Unit	$
Plant Operation and Maintenance	
Average net cash required	
(2.7% of annual operating expenses, including fuel = 0.027 x $10,961,000)	295,957
Materials and supplies in inventory	
(25% of annual cost of maintenance, materials and supplies = 0.25 x $864,400)	216,100
	512,057
Fuel Cycle Operations	
Core fabrication	
(60% of core fabrication = 0.60 x $7,332,000)	4,399,200
Nuclear materials	
(assumed leased from U.S. AEC at 4.75%/yr)	none
Total Working Capital	4,911,257