Solid DC Submarine Cable Insulated with PPLP (Polypropylene Laminated Paper)

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Abstract

Since 1970, SUMITOMO Electric has developed PPLP (Polypropylene Laminated Paper), the only one new insulating material with high dielectric strengths and low loss that can replace conventional cellulosic kraft paper. Many PPLP insulated oil-filled cables have already been installed in up to 500 kV AC and DC transmission lines and a long-term demonstration test of as high as 800 kV AC cable was successfully completed at IREQ's test-yard of Hydro Quebec, Montreal, Canada in 1993.
This paper introduces the application of PPLP to long-distance large-power Solid DC submarine cable and its outstanding merits, taking the Bakun Project for instance, and stresses the importance of trying to make use of the "Kyoto Mechanism" or CDM (Clean Development Mechanism) based on the "Kyoto Protocol" to create clean power huge projects.

1. Overview of Applications of PPLP Cable

Figure 1 shows the construction of PPLP which is made of extruded PP film sandwiched with kraft papers on both sides. Thanks to PP film and the combination of PP film and kraft paper, PPLP has higher AC, Impulse and DC breakdown (BD) strengths as well as lower dielectric loss than conventional kraft paper.
Figure 2 gives the state-of-the-art of underground and submarine cable. The most advanced six cables with liquid insulation out of all nine kinds of cables are composed of PPLP. Sumitomo Electric is now keenly implementing R& D on PPLP Solid DC cable and HTS AC/DC cable.

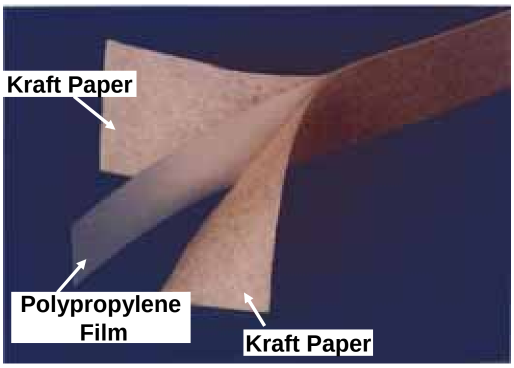


Figure 1. PPLP

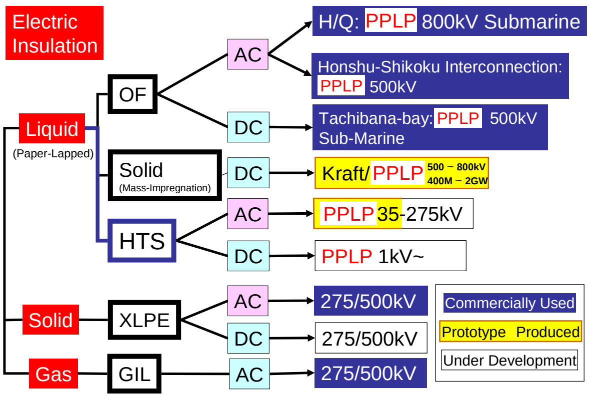


Figure 2. Underground Transmission Cable

Major applications of PPLP OF cable in Asia are summarized in Table 3, which says that PPLP OF cable has already been well-known among Asian countries and has become a de facto standard in the field of underground transmission cable.

Table 3. Major Applications of PPLP OF Cable in Asia

Country	Customer	Voltage／Size (kV) (mm²)	Commissioning Date	Others
Singapore	Power Grid	400 × 2,000	2000	
Thailand	MEA	230 × 2,500	2002	
Hong Kong	HEC	275 × 1,100	1991	
Australia	TransGrid	330 × 1,600	2004	
Japan	KEPCO	275 × 1,500	1982	
Japan	EPDC	550 × 2,500	1993	Along Seto-Bridges
Japan	KEPCO EPDC	±500 × 3,000	1999	DC Submarine Cable
(Canada)	H／Q (IREQ)	800 × 2,000	1990	Demonstration

2. DC BD Mechanism of PPLP

DC electric field distribution changes very smoothly in PPLP in accordance with ρ-distribution as shown in Fig. 4. Since ρ of PP is much higher, DC stress is mostly imposed on the impregnated PP film which is intrinsically strong against such stress as illustrated in Fig. 5.

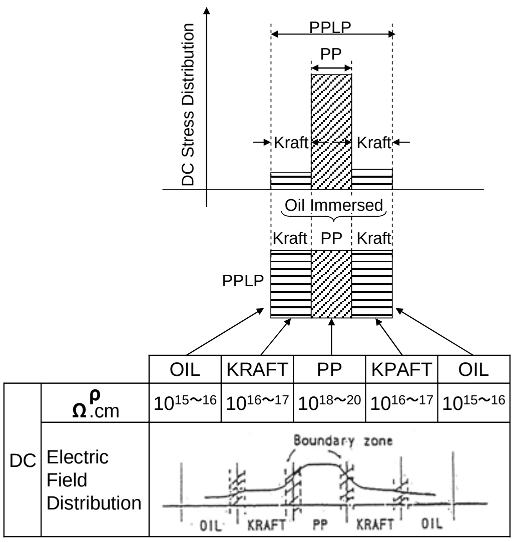


Figure 4. ρ & Electrical Field Distribution of PPLP

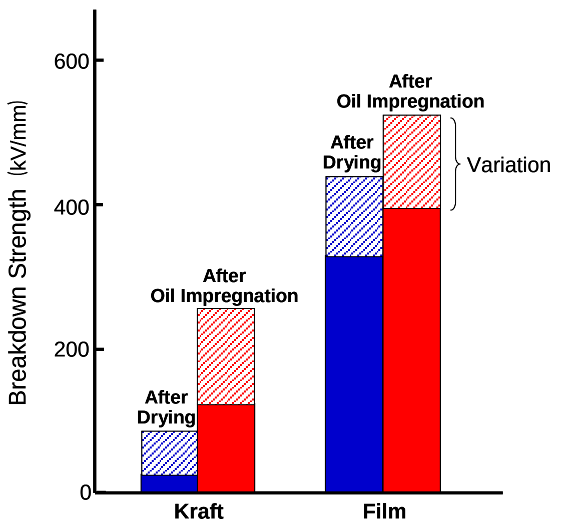


Figure 5. Comparison of Electric Breakdown Strength between Kraft and Film

In contrast with kraft paper where BD mechanism is same with Imp. and DC, hence BD stress is almost same in Imp. and DC, in case of PPLP, BD occurs in the kraft portion of PPLP with Imp. and in the PP portion of PPLP with DC, hence DC BD stress is higher than Imp. BD stress as shown in Fig. 6.
Table 7 offers the comparison of BD mechanism and BD stress between kraft paper insulated OF cable and PPLP insulated OF cable for each voltage wave form, in which the superiority of PPLP over kraft paper can clearly be understood.

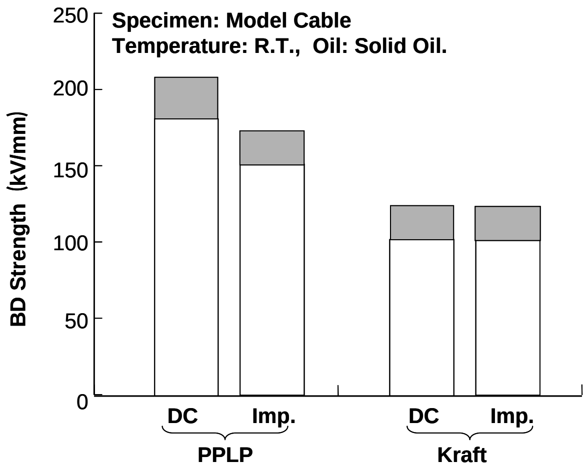


Figure 6. DC & Imp. BD Strengths of PPLP & Kraft

Table 7. Comparison of Breakdown Mechanism and Breakdown Stress between Kraft and PPLP OF Cable

Wave Form		Kraft OF Cable	PPLP OF Cable
AC	Mechanism	Discharge of oil of oil-gap	
	Stress	40～50	50～60
		（εk/εPPLP 3.4／2.8 1.2） ［Subject to “Oil-pressure Effect”］	
Impulse	Mechanism	BD of Kraft-tape	BD of oil of oil-gap ［Subject to “Polarity Effect”］
	Stress	100	130
DC	Mechanism	BD of Kraft-tape	BD of PP-tape of PPLP
	Stress	100 （DC BD Imp. BD）	180 （for Model Cable） （DC BD 1.4×Imp. BD） ［Proportional to PP ratio］

When conceived the concept of the combination of PPLP as a main insulation and two thin kraft paper layers, one applied onto the conductor and the other just beneath the metal sheath, the world biggest-ever and very tough DC ±500 kV 1×3,000 mm^2 submarine cable was achieved for Kii-channel interconnection submarine cable in Japan in 2000, due to the preferable ρ-grading for DC stress distribution and also the preferable ε-grading for Imp. stress distribution as given in Fig. 8. This cable can transmit as high as 1.4 GW/cable (2,800 A/cable).

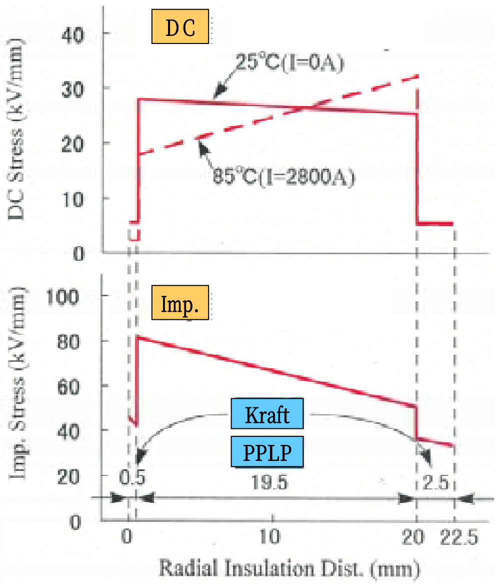


Figure 8. DC 500kV 1×3,000mm^2 Submarine cable with PPLP/Kraft Insulation (22.5mm)

3. PPLP DC Solid Submarine Cable

For very long distance power transmission, only Solid (MI: mass-impregnated; ND: Non-draining) DC cable can be used because it is impossible to feed insulating oil from each end of a cable. Therefore very high viscous oil has been used for conventional kraft paper Solid DC cable under relatively low permissible conductor temperature (Tmax), say, around 50°C, in order to prevent oil-migration. To the contrary, relatively low viscous oil at high Tmax, say, around 80°C, can be applied to PPLP Solid DC cable, since PP of PPLP does not allow oil to flow through it as shown in Fig. 9 and lets weak kraft papers of PPLP be free from DC stress. Moreover the increase of PP ratio of PPLP in order to improve DC BD stress as shown in Fig. 10 is, at the same time, effective for oil-migration hardly to occur.

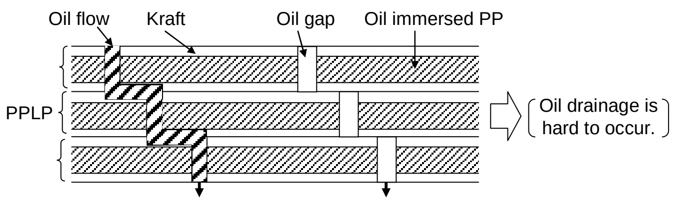


Figure 9. Oil draining in PPLP insulation

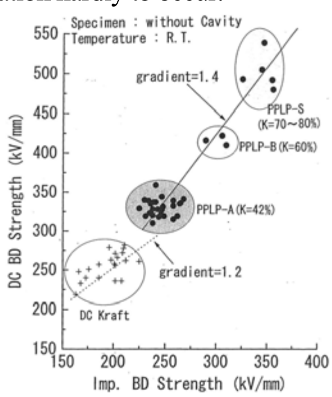


Figure.10. Relation between Imp. BD and DC BD

Figure 11 indicates the excellent innovation achieved by PPLP Solid DC cable which is usable with higher voltage and at higher Tmax.

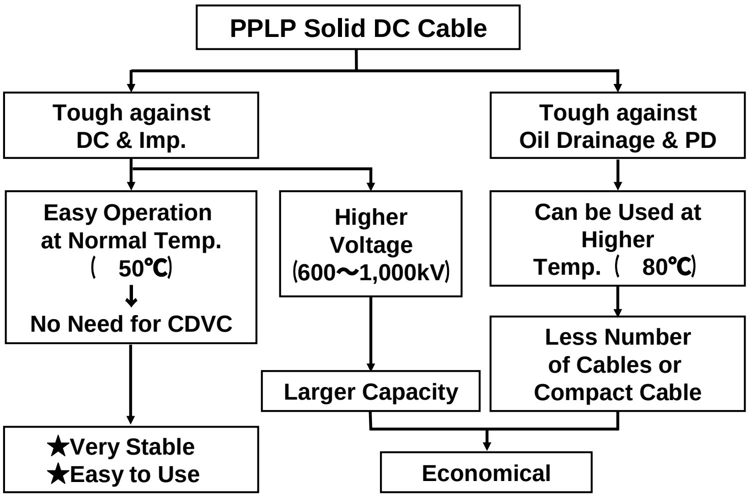


Figure 11. PPLP Solid DC Cable

Sumitomo Electric has already implemented a demonstration field test on a prototype of PPLP Solid DC Cable as given in Fig. 12.

Construction

＊Cond.: 2,000mm^2
＊Insulation: Kraft/PPLP-A (PP ratio:40%) /Kraft
＊Thickness: 24mm
＊Insulation Oil: Medium Viscosity Oil

	Conventional Kraft Solid	PPLP Solid
Max. Voltage (kV)	450	600-800
Max. Current (A)	1,300	2,000
Capacity (MW)	600	1,200–1,600
Target	600kV :1,200MW (In Case of PPLP, Possibly 800kV 2,000MW)	

Test Results

＊100℃ Heat Cycle
＊DC -800kV OK

Future: PPLP with higher PP Ratio (80%) shall be tested

Figure 12. Test on PPLP 800kV Solid (MI) DC Cable at SEI's Kumatori Testing Station

Table 13 shows the comparison between conventional kraft cable and new PPLP Sold DC cable for ±250 kV and 1,200 A use. Figure 14 indicates that PPLP can achieve a more compact and economical cable system.

Table 13. PPLP or Kraft Solid DC Cable for Prospective Hokkaido-Honshu ±250kV Project

			Kraft	PPLP
Voltage (kV)			±250	
Ampacity (A)			1,200	
Highest Cond. Temp. (°C)			50	80
Design Stress (kV/mm)		DC	25	40
		Imp.	65	80
Construction	Conductor	Size (mm²)	1,400	800
		Dia. (mm)	45	34
	Insulation Thickness (mm)		16	13
	Outer Dia. (mm)		87	70
	Equiv. Thickness te (mm)		12.1	9.7
Performances	Withstand Test (with Heat Cycle)		-500kV (1Week) →+500kV (1Week) → ±375kV (Polarity Reversal 1Week) → Cut & Electrical Test	
	DC BD (kV/mm)	R.T.	118	168
		Hot	102	161
	Imp. BD (kV/mm)	R.T.	99	144
		Hot	90	128
	DC+Imp. BD (kV)	R.T. (-DC+Imp.)	1,100 (k=0.4)	1,350 (k=0.2)

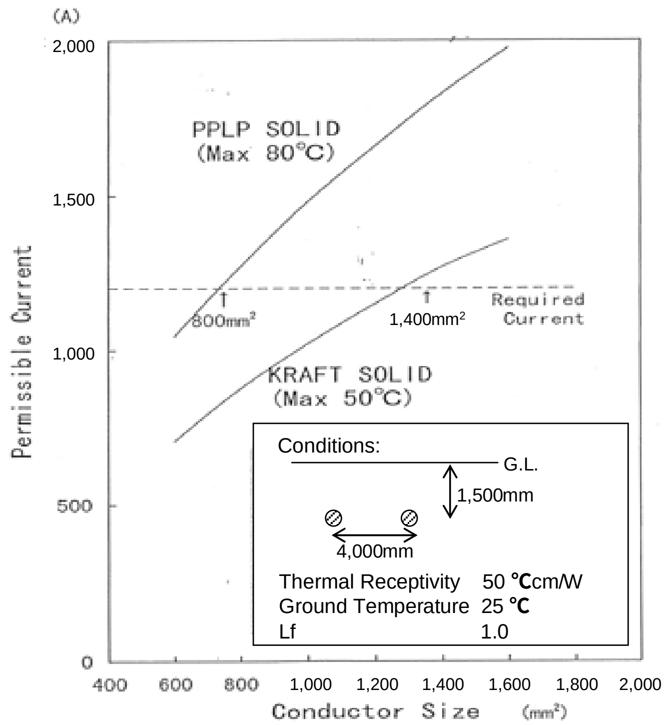
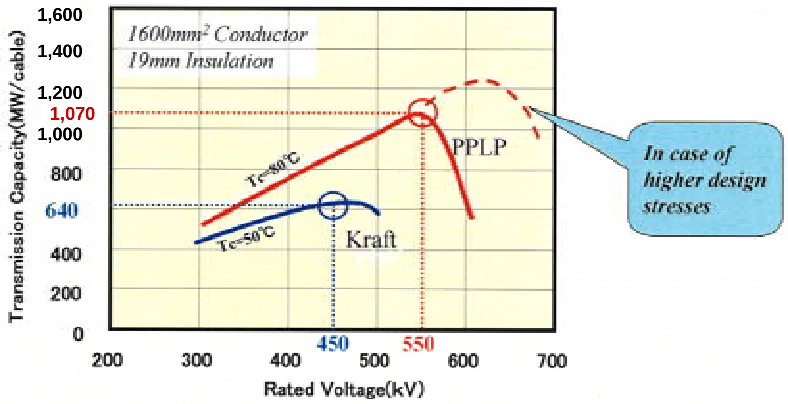


Figure 14. PPLP or Kraft Solid DC Cable of 250kV 1×1,200A Project

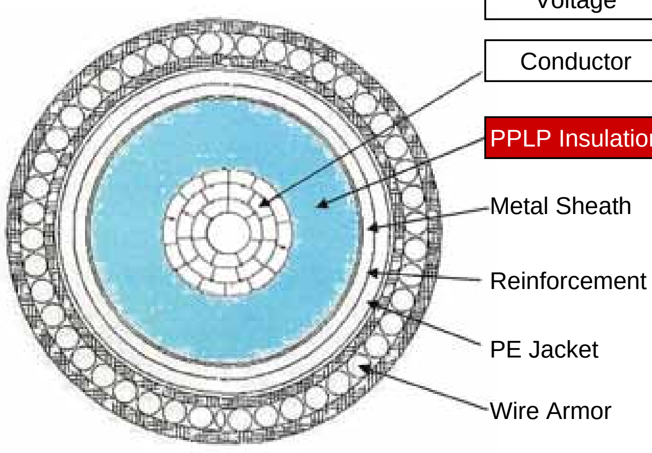
Figure 15 gives the target performance of PPLP Solid DC cable when following the current CIGRE Recommendation for designing DC cable. The 16.5 mm thick PPLP insulated Solid DC cable with a conductor of 1,800 mm^2 has an optimal point of voltage and current combination in terms of transmission power. It is impossible to increase transmission power so far as conventional kraft paper is used. While a PPLP cable can transmit 1 GW in 500 kV even in accordance with the conservative current CIGRE Recommendation which should essentially be applicable solely to cellulosic kraft paper Solid DC cable.
The introduction of DC BD mechanism for PPLP insulation in addition to the field test results on a prototype of PPLP Solid DC cable shown in Fig. 12 strongly suggests that the current CIGRE Recommendation should promptly be revised to fairly enjoy the merits derived from newly developed technologies based on the new cable concept backed by such a new insulation material as PPLP.

	PPLP Solid	Kraft Solid
DC working (Uo)	40kV/mm	25〜30kV/mm
Superimposed Imp. Voltage	100kV/mm	85〜90kV/mm
Max. Conductor Temp. (Tc)	80℃	50〜55℃
Transmission Capacity／cable	>1GW	<600MW



Construction of DC ±500kV 1GW PPLP Solid DC Cable

		(kV)
Voltage	±500	±550
		(mm²)
Conductor	1,800	1,600
		(mm)
PPLP Insulation	16.5	19



Diameter: Approx.135mm　Weight: Approx.52kg/m

Figure 15. Target Performance of PPLP Solid DC Cable

Here the combination of kraft paper layers and PPLP as a main insulation helps to reinforce weak points of Solid cable in the same way as shown in Fig. 16, through ρ-grading and ε-grading.

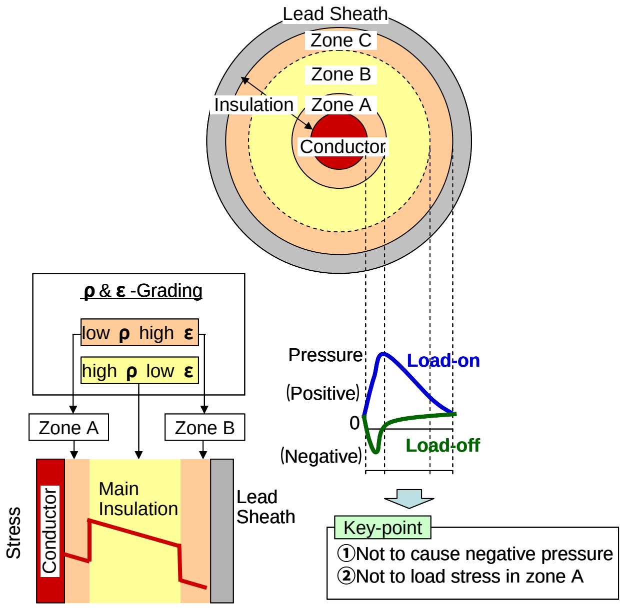


Figure 16. Countermeasures against Negative Pressure Arising at Load-off

4. Application of PPLP Solid DC Submarine Cable to Bakun Project

ASEAN countries have the plan of ASEAN Power Interconnection as shown in Fig. 17. In this plan, the Bakun Submarine Cable Interconnection between Sarawak and the Malaysia Peninsula crossing the South China Sea will work as a backbone. The plan shown in Table 18 was once conceived, in which conventional kraft Solid DC cable was specified to adopt, but postponed due mainly to economical difficulties.

The permissible ampacity is proportional to $\sqrt{\text{Tmax} - \text{To}}$, where To denotes the temperature of the sea and in case of the Bakun Project To is as high as around 30°C in contrast with around 5°C of the European sea. Around 50°C of Tmax for conventional kraft paper Solid DC cable is too low to realize fewer cables with more compact size in an economical way. The application of PPLP Solid DC cable will pave the new way for the realization of the Bakun Project in which Solid DC cable will have to run in the tropical hot sea. For example, three PPLP Solid DC cables operated at the same Tmax of 50°C as of conventional kraft Solid DC cable can secure the total amount of transmission power even in the case of an accident on a cable, since the remaining two PPLP cables can transmit the same power by operating them at 80°C in accordance with the simple calculation as follows: $2 \times \sqrt{(80-30)/(50-30)} = 3.16$. This means no need for a spare cable or shows that it is possible to replace three conventional kraft Solid DC cables with two PPLP Solid DC cables.

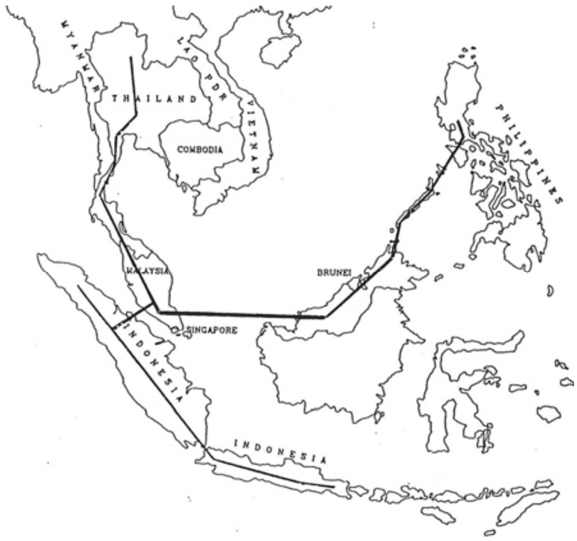


Figure 17. The prospect of ASEAN Power Interconnection

Table 18. Bakun Submarine Cable Project

<table>
<tr><th colspan="2">Items</th><th>Contents</th></tr>
<tr><td colspan="2">Customer</td><td>Bakun Hydro Electric Co.</td></tr>
<tr><td colspan="2">Hydraulic Power</td><td>2,520MW (16,785GWh／Year)</td></tr>
<tr><td rowspan="2">Transmission Cable</td><td>OHL</td><td>B･H･P･P～TG. DATU 660km 2 Bipole (4 Cables)</td></tr>
<tr><td>Submarne cable</td><td>TG. DATU～TG. SEDILI 670km 4～6 Cables
±500kV 1×2,100mm^2 1,420A (710MW) ／Cable;
Loss: 4.5%
Total Transmission Power: 2.13GW</td></tr>
<tr><td colspan="2">Construction Period</td><td>7 years</td></tr>
<tr><td colspan="2">Predicted Construction Cost</td><td>5 B$</td></tr>
</table>

The "Kyoto Protocol" came into effect on February 16, 2005 and Japan, only one country in Asia, should reduce CO_2 by 6 % by 2010. The Japanese government already decided to attain 1.6 % through the application of the "Kyoto Mechanism"or in this case, CDM (Clean Development Mechanism). There have been no clear criteria so far for the "Kyoto Mechanism." However, it is fully conceivable to apply the CDM funds to the Bakun Project, because hydraulic power is quite free from CO_2. On the assumption that oil thermal power of 2.13 GW can be replaced by the same hydraulic power of the Bakun Project, Japan could obtain the CO_2 reduction right of 0.89 % as shown in Table 19. Assuming the CO_2 trade price to be 10 \$/ton-CO_2, then the Bakun Project can earn the total amount of the CDM money per year of 105 M$, which can be converted to the Discount Present Value using a compound interest rate formula as shown in the same Table. The combination of the interest rate of 3 to 5 % and the operation year of 20 to 30 years will produce the Discount Present Value of 1,313 to 2,058 M$ which might probably cover the construction cost of submarine cables for the Bakun Project, "independently of power selling benefit"

Table 19. CDM (Clean Development Mechanism) for Bakun Project

<table>
<tr><th colspan="2">Items</th><th>Contents</th></tr>
<tr><td colspan="2">Transmission Power</td><td>2.13GW (14,187GWh/year)</td></tr>
<tr><td rowspan="3">CO_2 Reduction</td><td>CO_2 Emission
(g-CO_2/kWh)</td><td><table><tr><td>Charcoal Thermal Power</td><td>975.2</td></tr><tr><td>Oil Thermal Power</td><td>742.1</td></tr><tr><td>Hydraulic Power</td><td>11.3</td></tr></table></td></tr>
<tr><td>(From Oil to Hydro.)</td><td>742.1−11.3=740.8 g-CO_2/kWh</td></tr>
<tr><td>Japanese Merit</td><td>Japanese Government's Policy:
To attain ▲1.6% of 1,237Mton-CO_2 through CDM

14,187GWh×740.8g-CO_2/kWh =11Mton-CO_2
⇨ 11/1,237×100=0.89%
} Approx. Half of ▲1.6% can be obtained
(cf From Charcoal to Hydro.:▲1.1%)</td></tr>
<tr><td colspan="2">Assumed CO_2 Trade Price</td><td>10$/ton-$CO_2$ (~ Could be up to 60$/ton-$CO_2$)</td></tr>
<tr><td colspan="2">Total Amount of CDM Money per Year</td><td>14,187GWh/year×740.8g-CO_2/kWh×10$/ton-$CO_2$=105M$/year</td></tr>
<tr><td colspan="2">Discount Present Value (M$)</td><td><From Oil to Hydro.><table><tr><td></td><td></td><td colspan="3">Years</td></tr><tr><td></td><td></td><td>10</td><td>20</td><td>30</td></tr><tr><td rowspan="2">Interest</td><td>3%</td><td>893</td><td>1,565</td><td>2,058</td></tr><tr><td>5%</td><td>809</td><td>1.313</td><td>1,617</td></tr></table><From Charcoal to Hydro.><table><tr><td></td><td></td><td colspan="3">Years</td></tr><tr><td></td><td></td><td>10</td><td>20</td><td>30</td></tr><tr><td rowspan="2">Interest</td><td>3%</td><td>1,162</td><td>2,037</td><td>2,679</td></tr><tr><td>5%</td><td>1,052</td><td>1,709</td><td>2,105</td></tr></table></td></tr>
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It can keenly be insisted that it should be worth while to consider the application of Japan's ODA (Official Development Assistance) as the CDM funds for the Bakun Project comprised of PPLP Solid DC submarine cable.

5. Conclusion

PPLP is the only one new insulation material that has been put into practical use and replaced kraft paper insulation for power cable. The BD mechanism of PPLP cable is different from that of conventional kraft paper cable in Imp. and in DC. Solid DC cable insulated with PPLP with a high PP ratio and impregnated with relatively low viscous insulating oil is the absolutely new advanced Solid cable based on a unique concept which requires the revision of the current CIGRE Recommendation, and will promise to create huge long-distance and large-power submarine power cable projects in the most economical way.

The 21st century characterized by the three key words, "Energy, Natural Resources and Environment" will need clean power generation like the Bakun Project. To create such a huge project, it is worth while to consider to use Japan's ODA as the CDM funds and to apply PPLP Solid DC cables to the Bakun Project.